# Surfaces, Interfaces, Spins – The age of Interface!

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# Why interface is important?

**"The interface is the device"**

**- Herbert Kroemer**

**Interface is the platform for creating exotic electronic states:**

- **Semiconductor heterostructure interface**: (*electron-electron interaction*)
  high mobility electron gas, fractional charge and statistics, topological order etc.

- **Oxide heterostructure interface**: (*correlated electrons*)
  high mobility electron gas, ferroelectricity, high temperature superconductivity etc.

- **Topological insulator surface**: (*spin-orbit coupling*)
  topological surface states

- **Combined interactions:** ferromagnetic, superconductivity, spin-orbit etc.
  → exotic electronic state: Majorana fermion
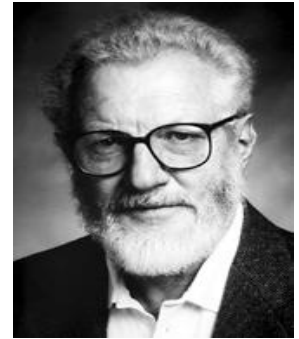
**Herbert Kroemer**

**Nobel Prize in Physics (2000)**

"for developing semiconductor heterostructures used in high-speed- and opto-electronics"
– Nobelprize.org

*Postdocs:*   **Ferhat Katmis,   Peng Wei,   CuiZu Chang**

**Yunbo Ou ,  Juanpedro Cascales**

**Visiting Scientist:  Yota Takamura**

## *Collaborators*

**mK transport** - **W.W. Zhao, .… J. Jain and M. Chan** - **Penn State**

**PNR**  -  **Valeria Lauter** -  **Oakridge Natl Lab**

**SQUID** - **Don Heiman** -  **Northeastern U**

**XAS, XMCD**   -  **John Freeland**  - **Argonne Natl Lab**

**XTEM**  -  **Biswarup Satpathy** -  **Saha Inst. Nucl. Physics**, **India**

**TIG/TI**  - **Chi Tang,   Jing Shi**  - **U of California Riverside**

**Theory** -  **Kyungmin Lee, Nandini Trivedi**  - **Ohio State U.**

- Spins  -  Spintronics: unconventional

- Spins  -  Superconductors

- Spins  -  Quantum coherent systems

The common platform

- **surfaces and interfaces!!**

# Towards Molecular Spintronics

*Why single molecules?*

❖ **Smallest well defined electronic units**

❖ **Chemically synthesize precisely designed properties, with atomic precision - tune tailored molecules !**

     **….. Unlimited possibilities ….**

❖ **Easily scalable**

*Add:* electron spin degree of freedom for spintronic functions within single molecular building block



**Acceptor groups**   **Donor groups**
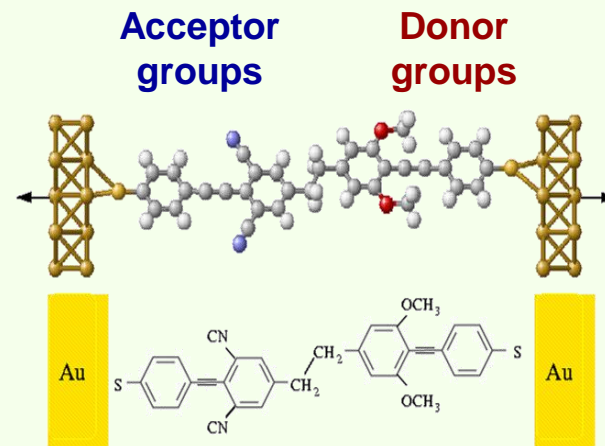
Molecular rectifier
Aviram and Ratner, (1974).

➡ **Towards single molecule information storage and sensing**

**We are at the beginning → Need of basic research!**

# Magnetoresistance in Co/ZMP (40 nm)/Py spin valve

$V_{dc} = 25$ mV and T = at 4.2K
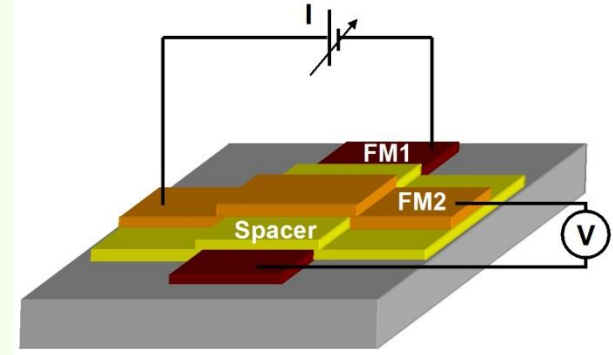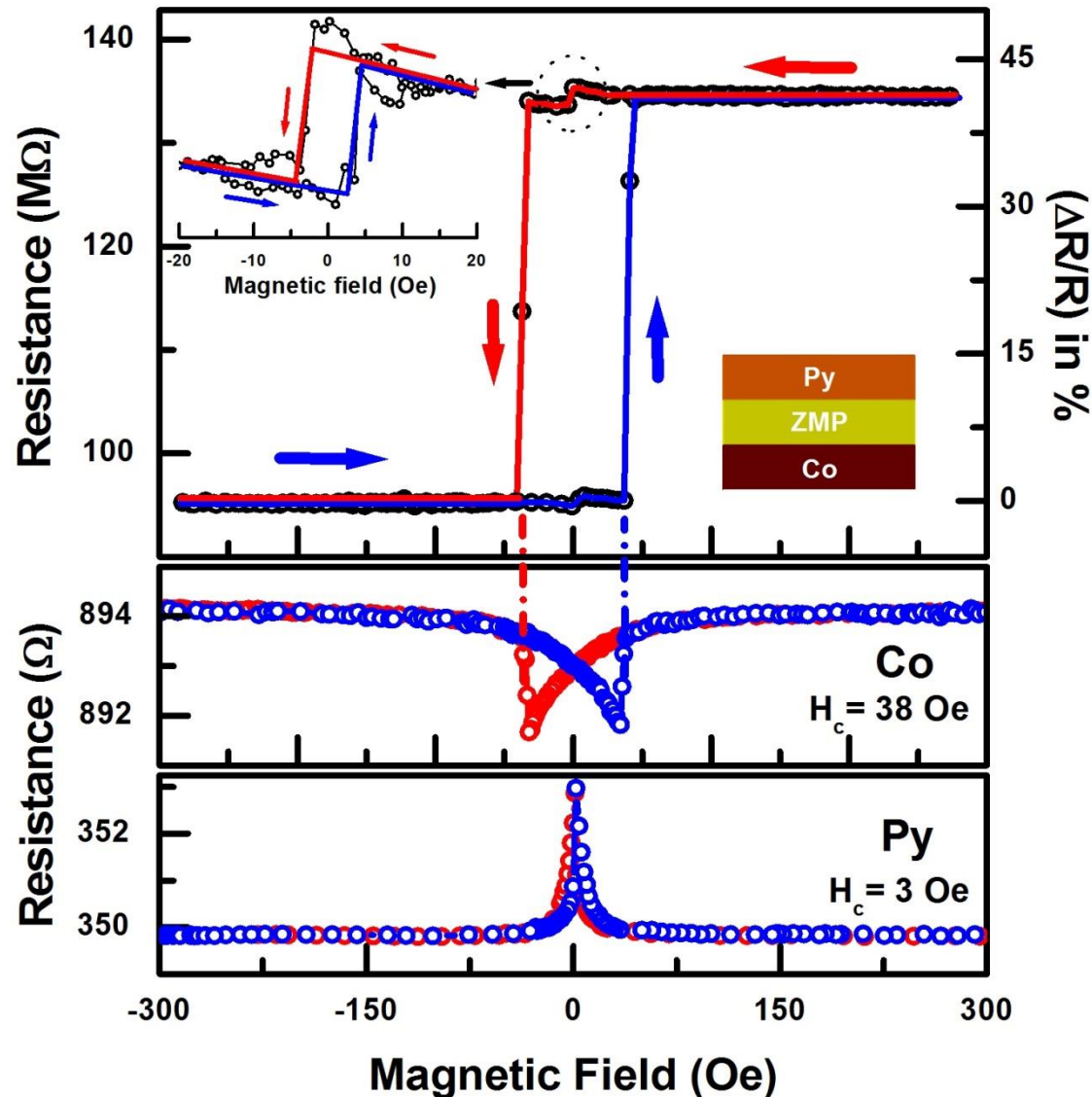


**Non-linear characteristics**
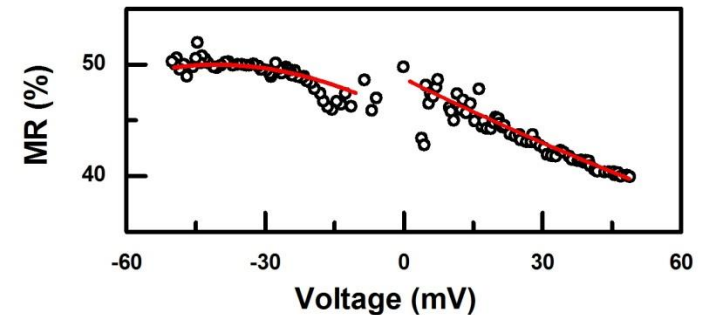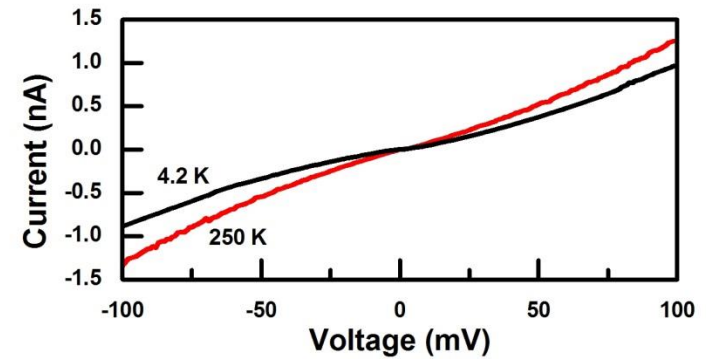


**Interface effect:**    K. V. Raman ….. JSM, Nature **493, 509 (2013)**

# Interface Effect: Confirmation!
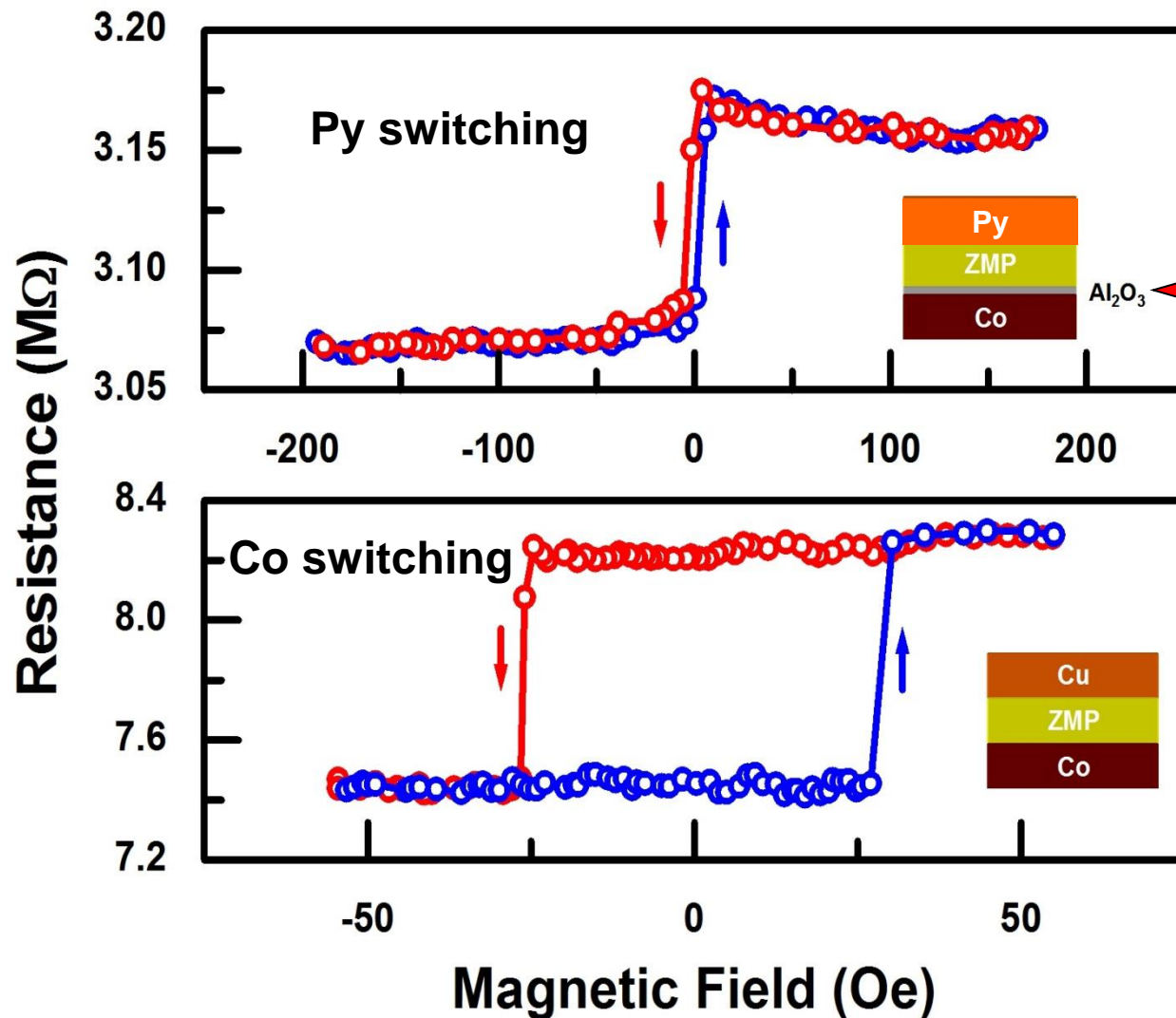


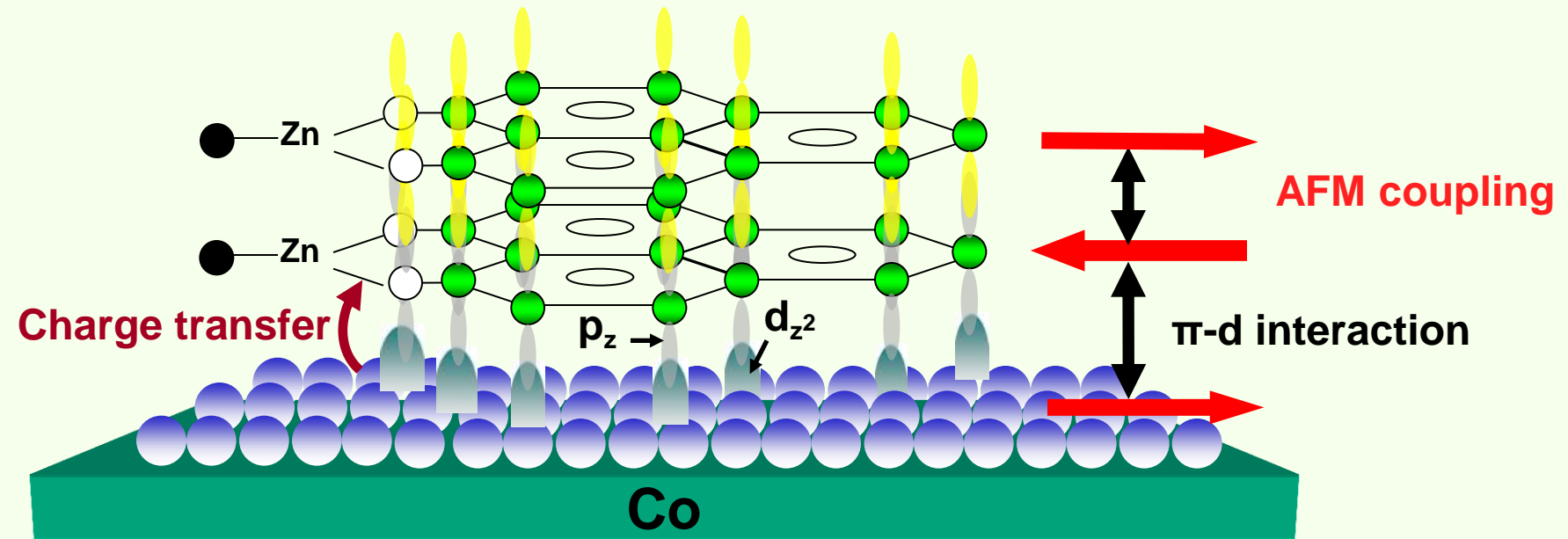**No induced FM** or antiparallel spin state at the bottom interface **with 0.3nm Al$_2$O$_3$ inbetween**

**No magnetism** or switching at the top interface **with Cu**

**No MR in**

**Cu/ZMP/Cu**

**A '*pinned magnetic layer*' exists at the interface**

# Interface phenomena
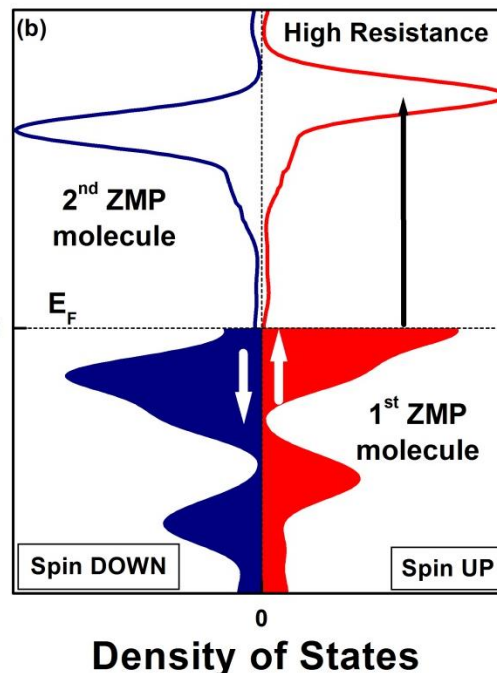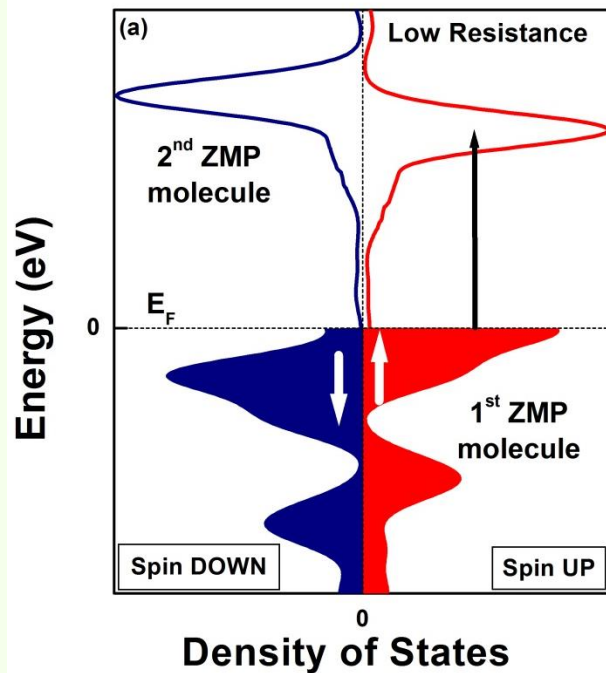
**Zinc methyl phenalenyl molecules over Co surface**

# Origin of IMR effect

Spin-filter molecule
Magnetic molecule
Surface Co
Bulk Co
Side view
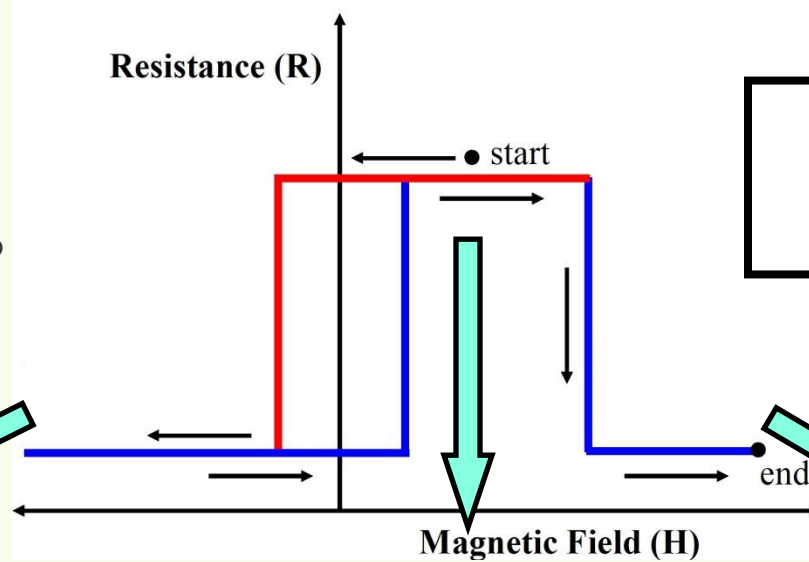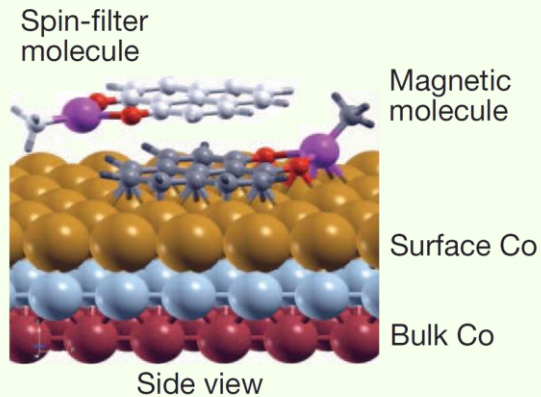
**Spin-filter injection/tunneling response**

**Theory by: N. Atodiresei**

**Resistance (R)**

● start

end

**Magnetic Field (H)**

(a) Low Resistance
2$^{nd}$ ZMP molecule
$E_F$
0
1$^{st}$ ZMP molecule
Spin DOWN
Spin UP
0
**Density of States**

(b) High Resistance
2$^{nd}$ ZMP molecule
$E_F$
0
1$^{st}$ ZMP molecule
Spin DOWN
Spin UP
0
**Density of States**

(c) Low Resistance
2$^{nd}$ ZMP molecule
$E_F$
0
1$^{st}$ ZMP molecule
Spin DOWN
Spin UP
0
**Density of States**

**Energy (eV)**
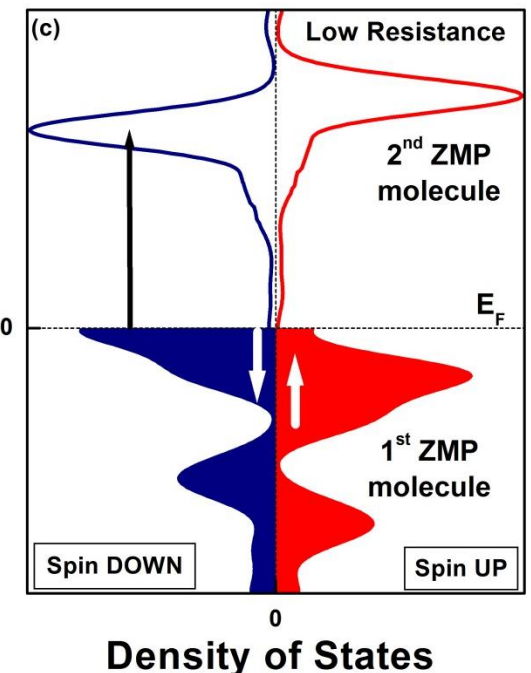
## Towards molecular spintronics …..

-   planar organic molecules (ZMP)

    →    magnetic & spin-filtering  -   room temperature

-   Molecules can store information as a classical bits i.e. '0' or '1' state

        Storage density may reach ~ 1000 TBytes/sq inch

## Technological advantages …

            Only one FM needed

Molecular 'bit' - integrated storage-sensing system

Molecules are ideal quantum dot systems
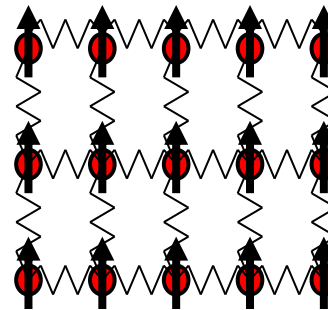
            - fabrication of scalable quantum memory registers

# Coexistence  of

# Superconductivity  *and*  Ferromagnetism !!

### Superconductivity
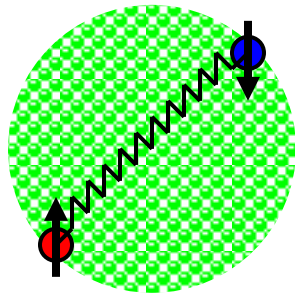


$E_{BCS} \sim 10^{-3}$ eV

### Ferromagnetism



$E_{EX} \sim 1$ eV

**SC and FM are competing spin ordering mechanisms**

*An unexpected observation ….*
*Ferromagnetic Ni is superconducting !!*

# Ferromagnetic Ni is also superconducting…

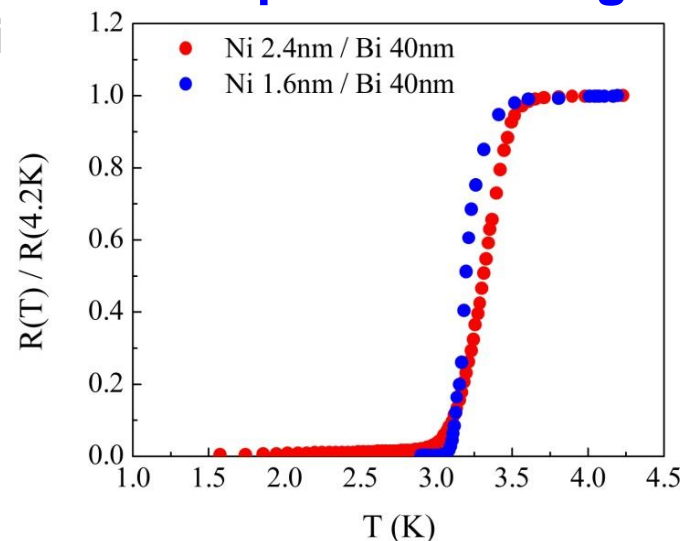**Normally Bi not a superconductor and Ni is a FM**
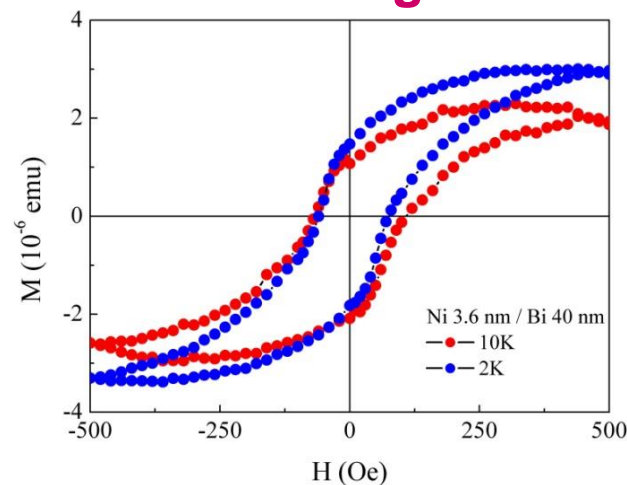
**Combining the two – Ni/Bi bilayers**

**SC and FM !**



Bi
Ni
$Al_2O_3$
Al
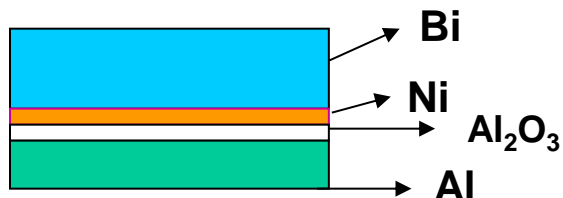
**SC present in *whole* Ni/Bi stack**

**Superconducting !**



**Ferromagnetic !**





Co 5nm/Al 4.2 nm/ ox / **Ni** $d_{Ni}$ / 40 nm Bi

$d_{Ni}$ = 4.2 nm    H = 0 T

$d_{Ni}$ = 3.6 nm    H = 0 T    H = 2.9 T



Ni 3.6 nm / Bi 40 nm
— 10K
— 2K
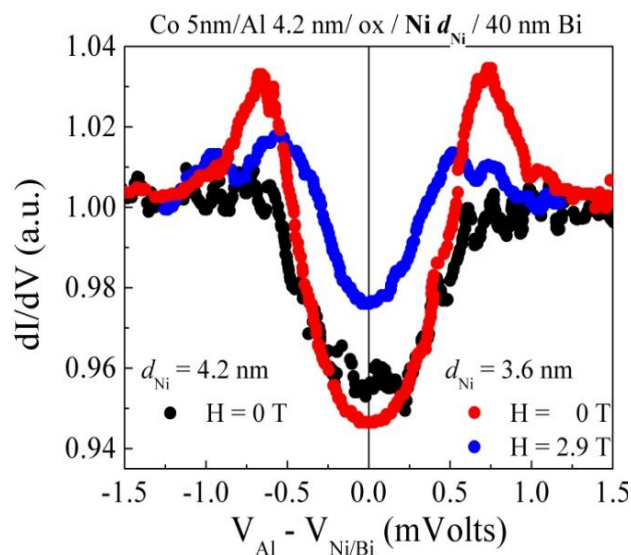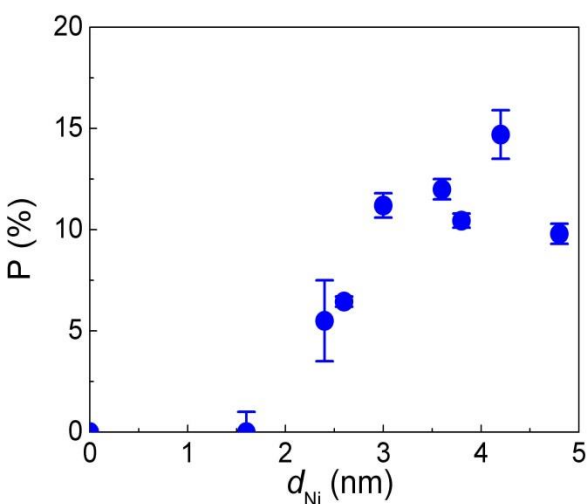
**Superconductivity and ferromagnetism coexist in Ni !!**

**Spin polarized current observed in a triplet SC?!**

# Superconductivity and ferromagnetism coexist in Ni/Bi bilayers !!
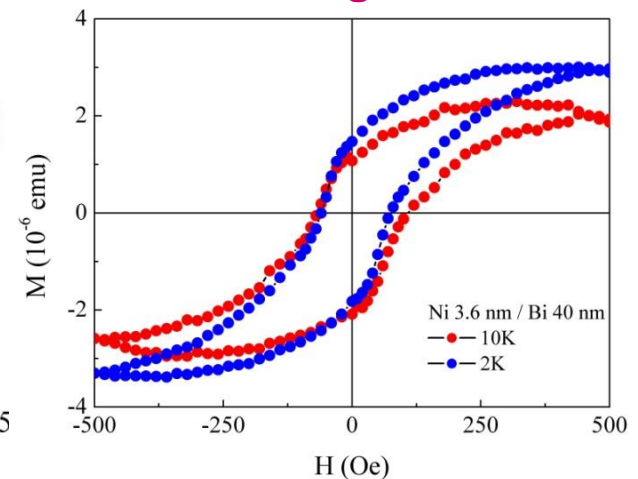
## Normally Bi not a superconductor and Ni is a FM
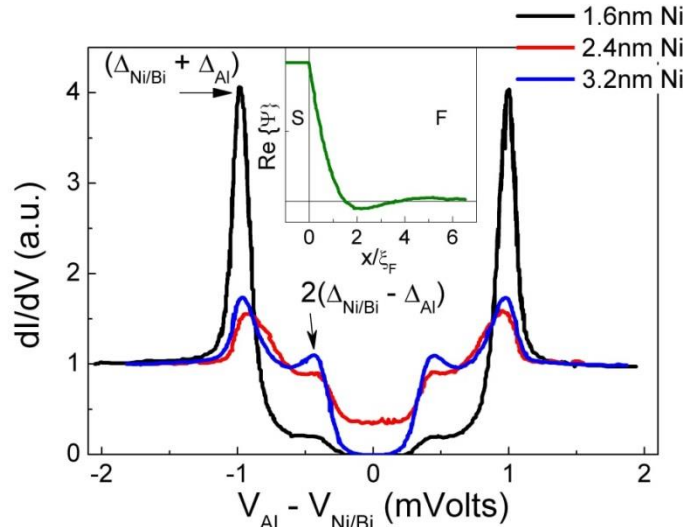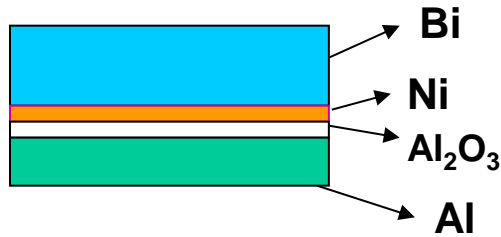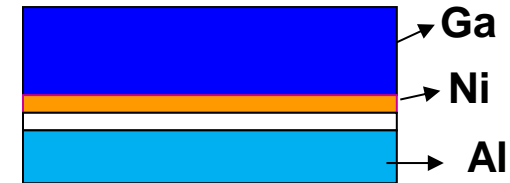
**Superconducting**
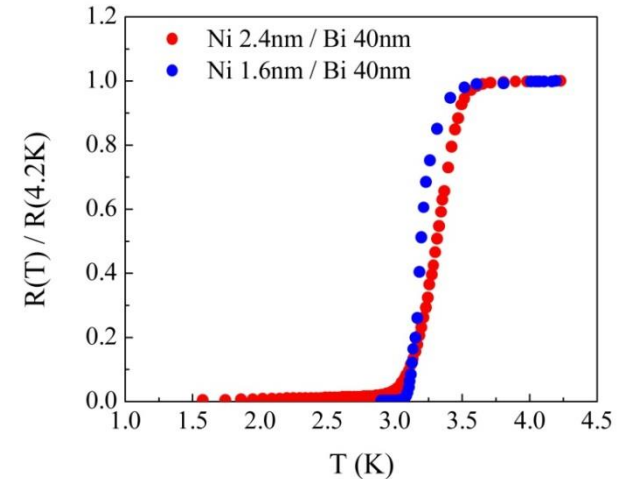
**Spin polarized!**
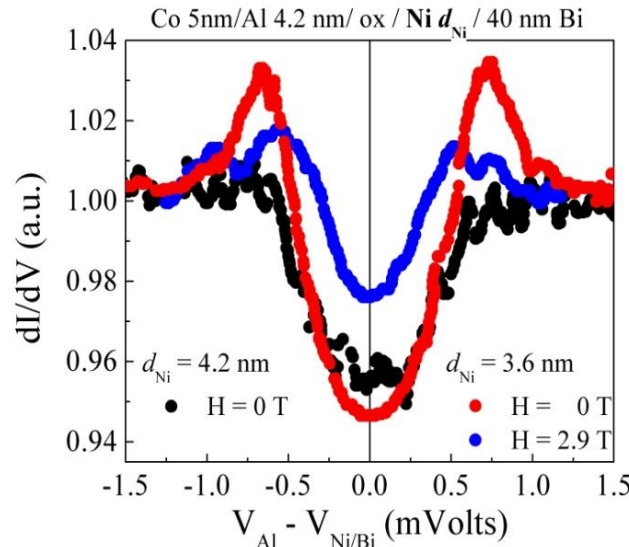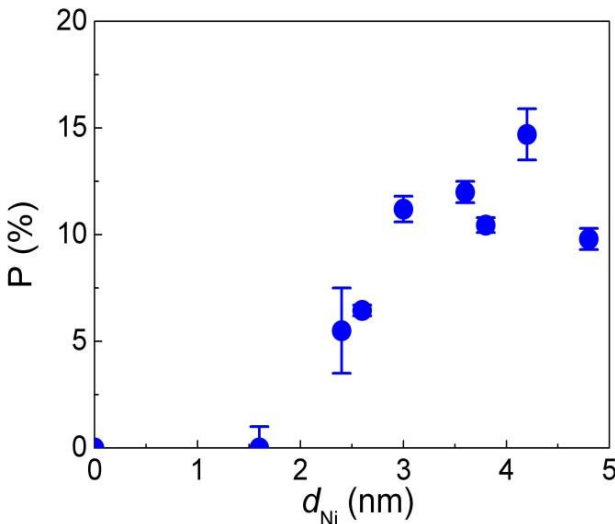
**Ferromagnetic !**

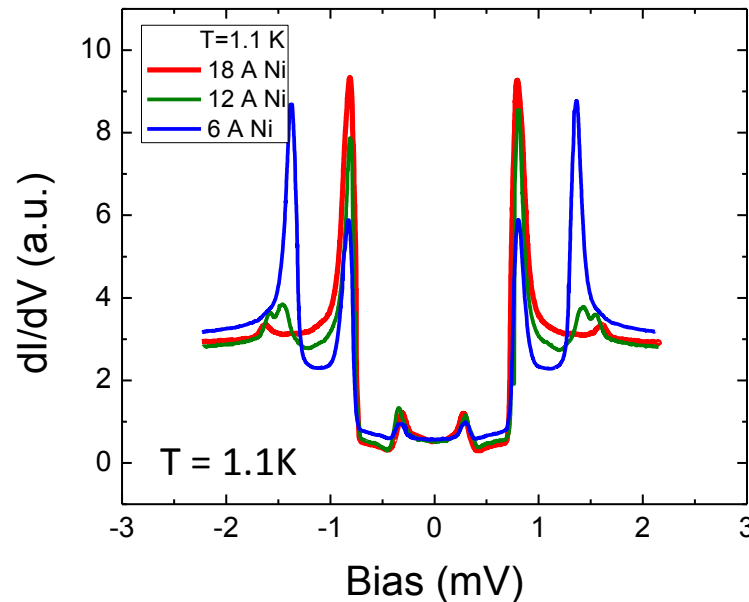**Spin polarized current observed - triplet paired SC?!**

Bulk Ga Tc = 1.08K
amorp Ga  Tc = 8.6K,  only stable < 20K



Ga
Ni
Al

*X* Ni/600A Ga film – **superconducts with Tc ~ 6.5K**

3-10057

**S – I – S Tunneling:  Three SC gaps !!**
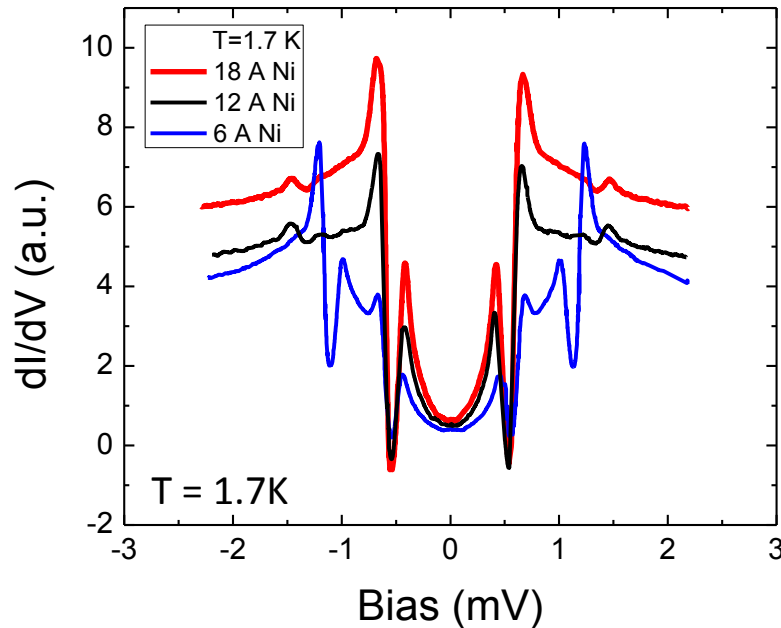


$T_C$ (Al) = 1.87K
At 1.7K
$2\Delta_{Al}$ = 0.26meV

*For 0.6nm Ni:*  $2\Delta_{Surface}$ = 1.14meV ;  $2\Delta_{Interface}$ = 2.28meV ;  $2\Delta_{Bulk}$ = 2.76meV

*For 2.4nm Ni:*  $2\Delta$ = 0.45meV ;  $2\Delta$ = 1.15meV ;  $2\Delta$ = 2.70meV

*$2\Delta/kT_C$ ~ 4.5 – strong coupled*

# Polarized Neutron Reflectivity results for Ni 56 A / Ga 600 A

**At 5K Meissner state:** field from the Ni side is screened at the Ga interface

**M profile: positive M in Ni ; negative in Ga**
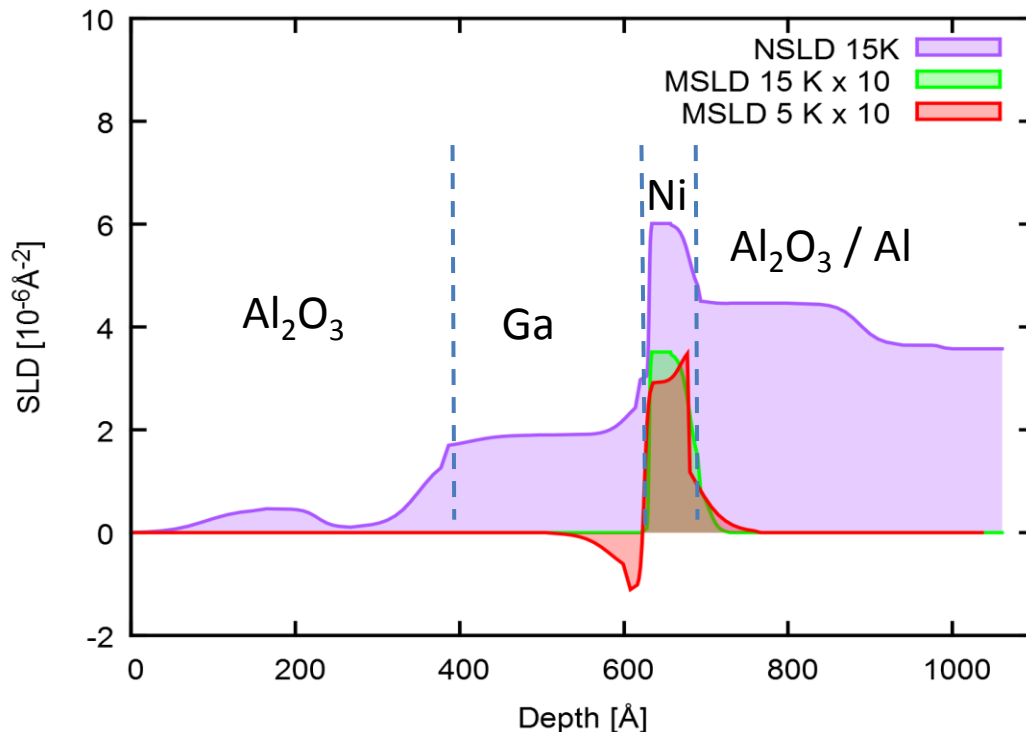


Samples zero field cooled to 15 K,
H 1 kOe applied – measure PNR
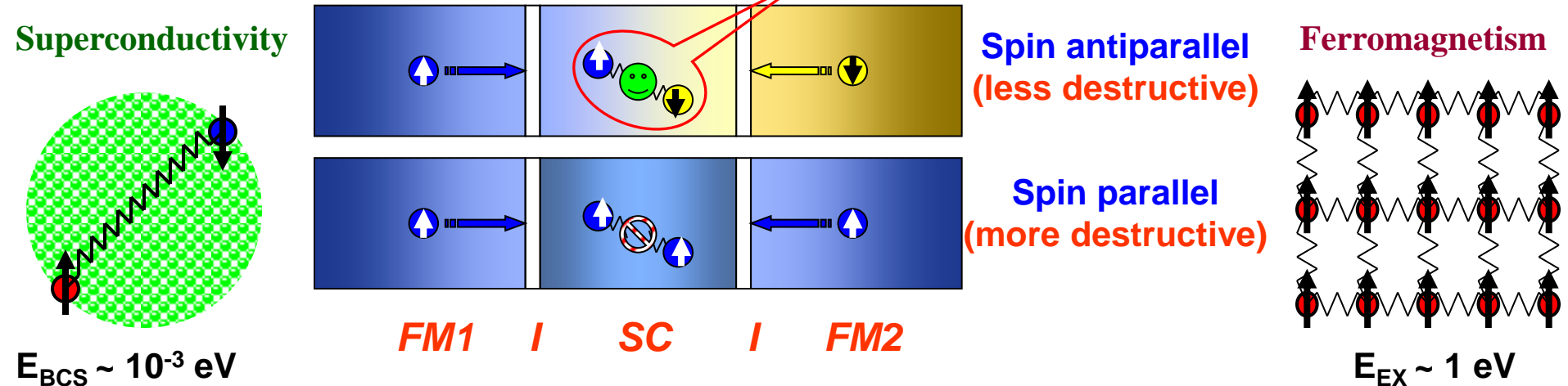ZFC to 5 K H = -150 Oe applied
H 1 kOe applied – measure PNR

**40 and 56 A Ni show clear magnetic signature
adjacent to 600A  Ga which is superconducting**

# Tuning superconductivity with spin current …

## SC and FM are competing spin ordering mechanisms



GuoXing Miao

**Cooper pairs**

**Superconductivity**

**Spin antiparallel (less destructive)**

**Spin parallel (more destructive)**

**Ferromagnetism**

*FM1    I    SC    I    FM2*

$E_{BCS} \sim 10^{-3}$ eV

$E_{EX} \sim 1$ eV

**Large MR is expected between ↑↑ and ↑↓ states**

*Reduced transparency:*    6 Fe / 1 $Al_2O_3$ / 4 Al / 1 $Al_2O_3$ / 6 Py  > 1000% MR

*Transparent interface:*    Epitaxial  6 Fe / 40 V / 6 Fe/1 CoO –  Infinite MR

**PRL 2007, 2008**

# Spin injection into superconductors
## *Over 1000% MR achieved!!*

**PRL 2007, 2008**

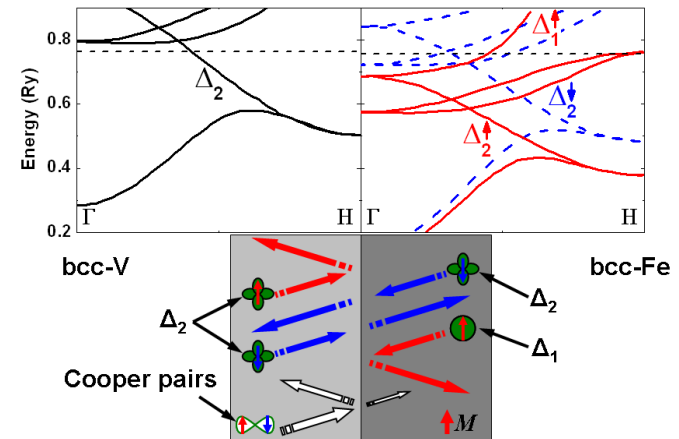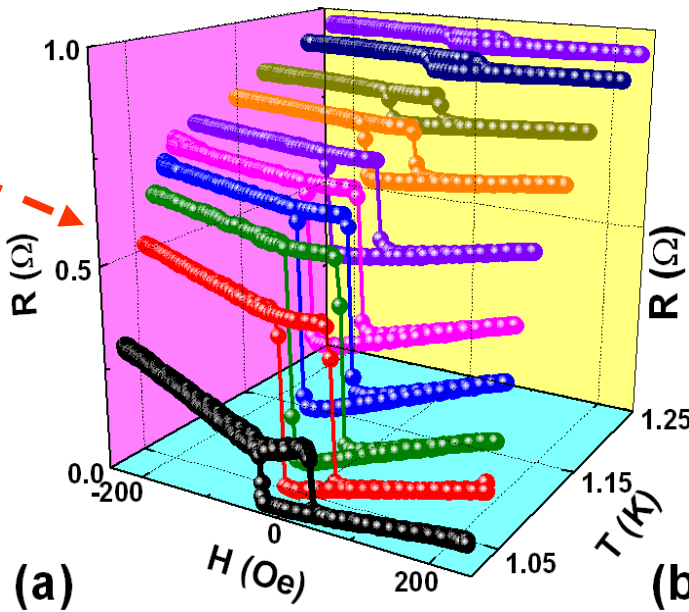**6 Fe / 1 Al$_2$O$_3$ / 4 Al / 1 Al$_2$O$_3$ / 6 Py**
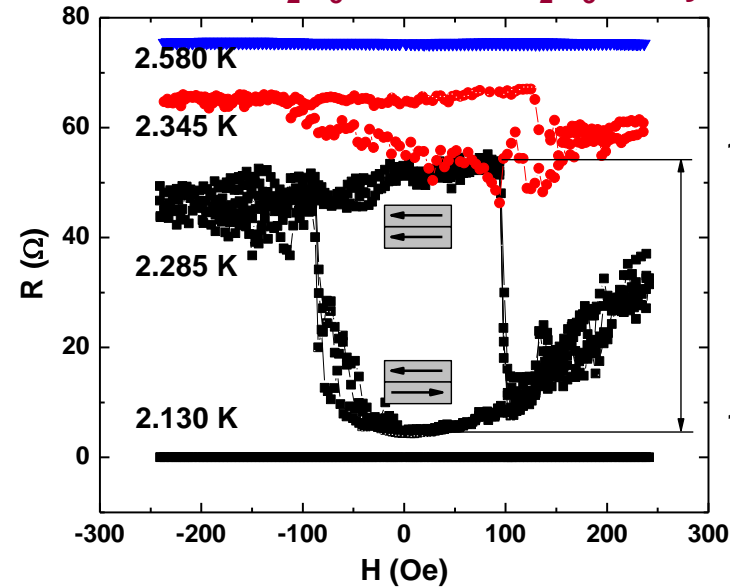
**Tc shifts for P and AP alignment**
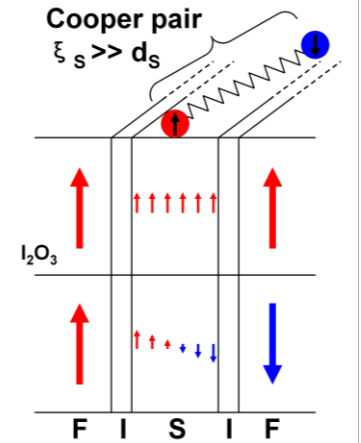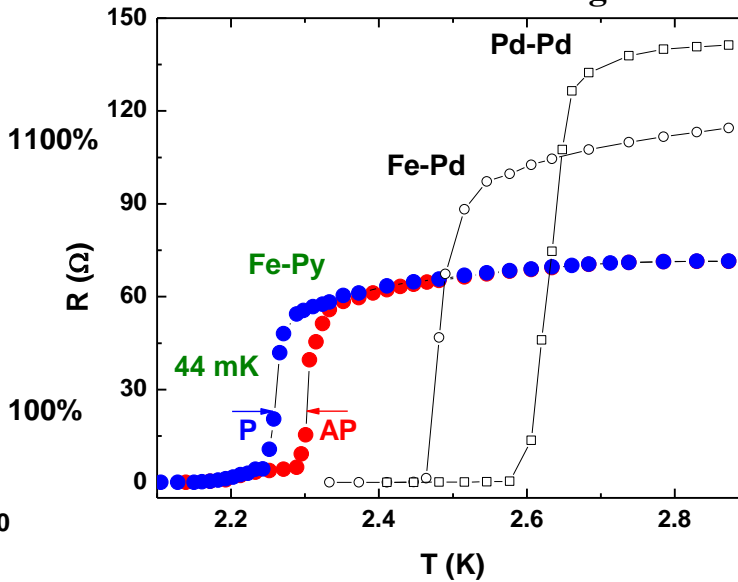


**BCC Heteroepitaxial Structure –**
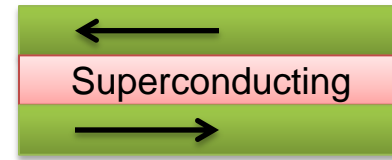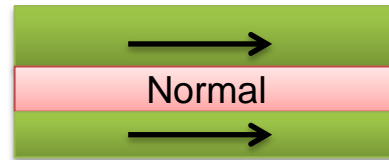**Band symmetry driven**
**Infinite MR achieved**

**(a)**

**(b**
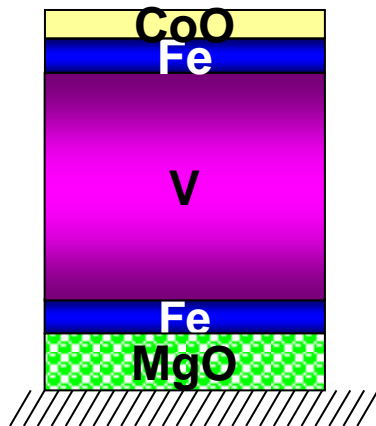
**Conduction band in V is of Δ$_2$ symmetry**
**Absent in Fe spin majority channel.**
**Opaque interface for Cooper pairs**

# De Gennes' prediction – 50 years ago

de Gennes, *Phys. Lett.* **23**, 374 (1966)

Ferromagnetic Insulator
Superconductor
Ferromagnetic Insulator

| Normal |
| Superconducting |

Finite $R$

$R = 0$

Average exchange field

$$\bar{h} = 2|\Gamma|S\left(\frac{a}{d_s}\right)cos\frac{\theta}{2}$$

From Tc change - exchange integral

$$\Gamma = 8.1\ meV$$
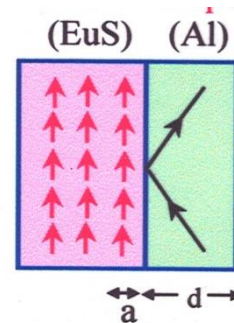
Average exchange field

$$\bar{h} \sim 13\ meV$$

**EuS**

**Al**

**EuS**

**Shows perfect superconducting spin switching effect**

**Equivalent external field ~200 T**

# Internal exchange field – Proximity effect at a ferromagnet insulator / metal interface
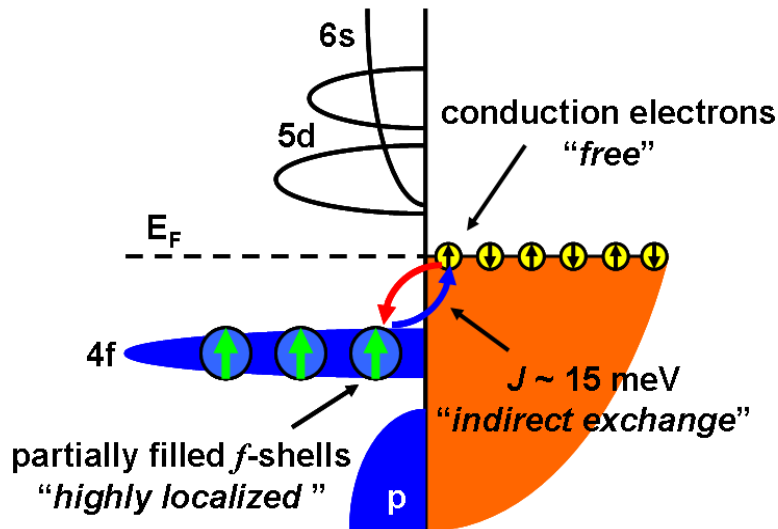
## Magnetic semiconductors EuS or EuO
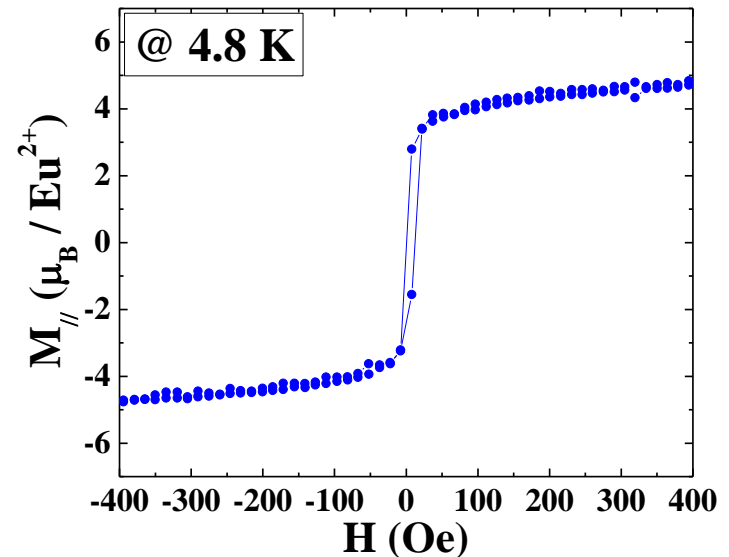
**Exchange Interaction between EuS and normal metal**



**EuS**
**Band gap $E_g$ = 1.64 eV**
$\Delta E_{ex}$ = 0.36



$$H_{EX} = -J \left( \overrightarrow{S_{e^-}} \cdot \overrightarrow{S_{Eu^{2+}}} \right)$$

**Magnetic Hysteresis**
**1 nm EuS thin film**



Sarma 1963
de Gennes, 1966
Tedrow et al PRL 1986

$\mathbf{B^* \propto 1 / d}$

# EuS/Al/EuS superconducting spin switch

**EuS/Al/EuS trilayer**

Normal

Superconducting

H = 0, remanent states



**Two resistance states**
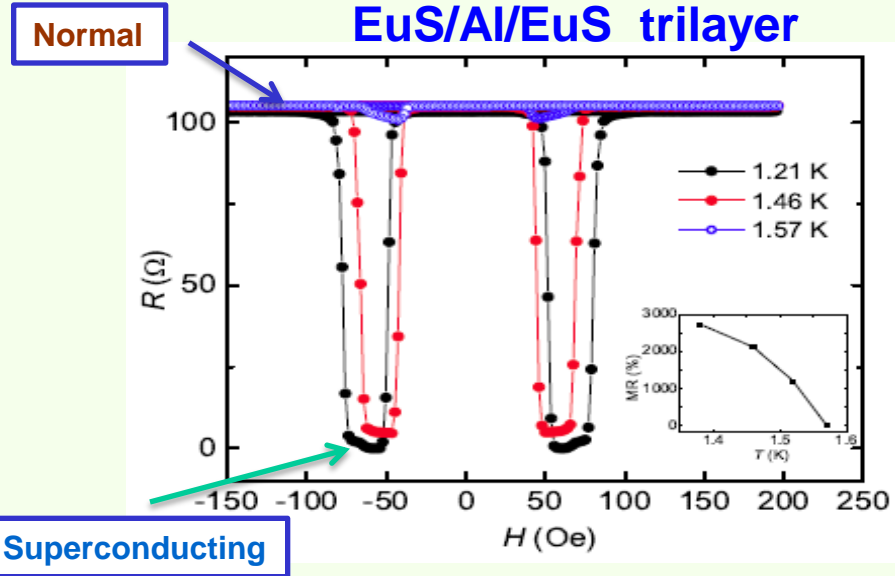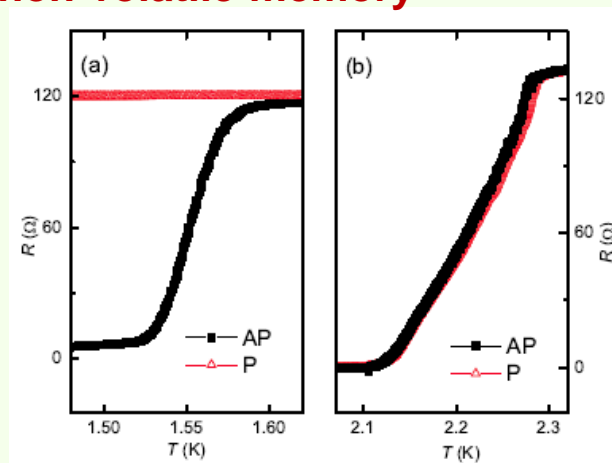
- Complete normal-superconducting transition
- **Infinite magnetoresistance (MR) ---**
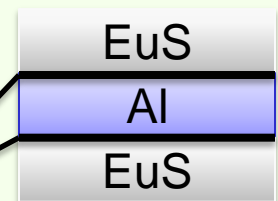  **Perfect switch, non-volatile memory**
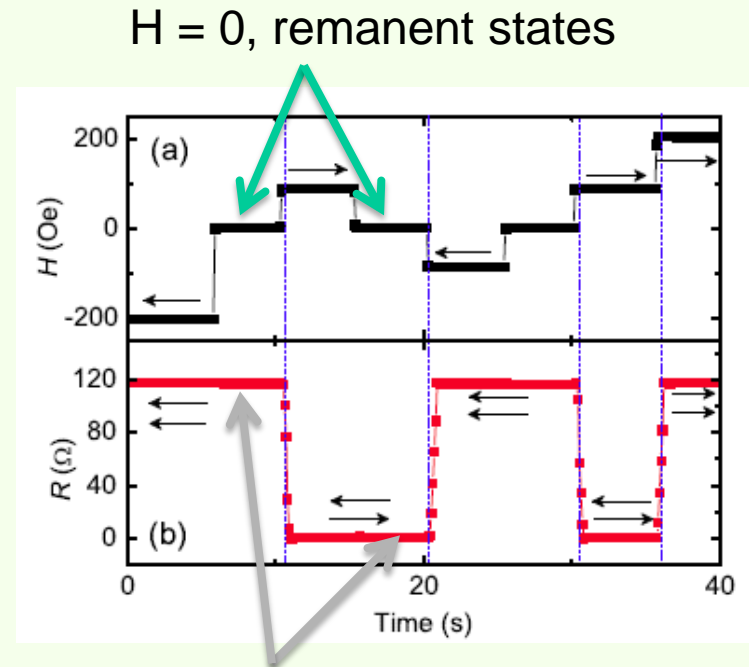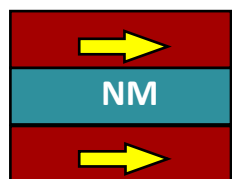
Supercond. transition

$T_C^{AP} > T_C^P$

EuS
Al
EuS
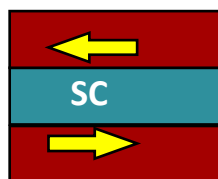
Suppresses proximity Exch.

EuS
Al
EuS

0.3 nm $Al_2O_3$

# Superconducting Spin Switch realized at higher temperatures

Parallel

Anti-parallel
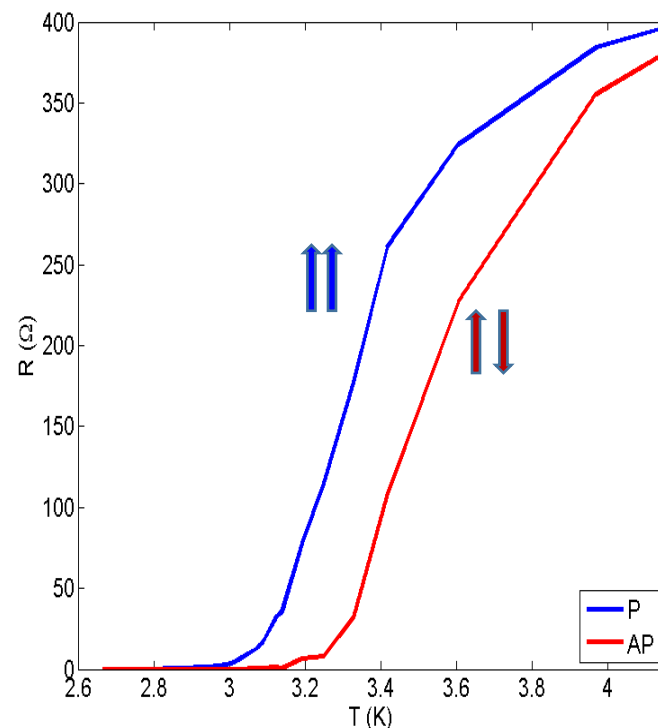
NM

SC

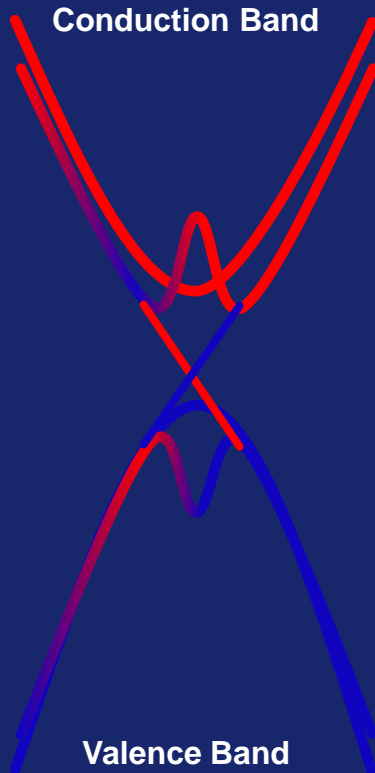SC:   Nb – 9.3K,  NbN – 15-16K

FMI:  GdN – ferromag. Tc 60K



Al$_2$O$_3$ 5 nm

GdN 13 nm

NbN 3.5 nm

GdN 27 nm

Al$_2$O$_3$ 5 nm

SiO$_2$

Si substrate
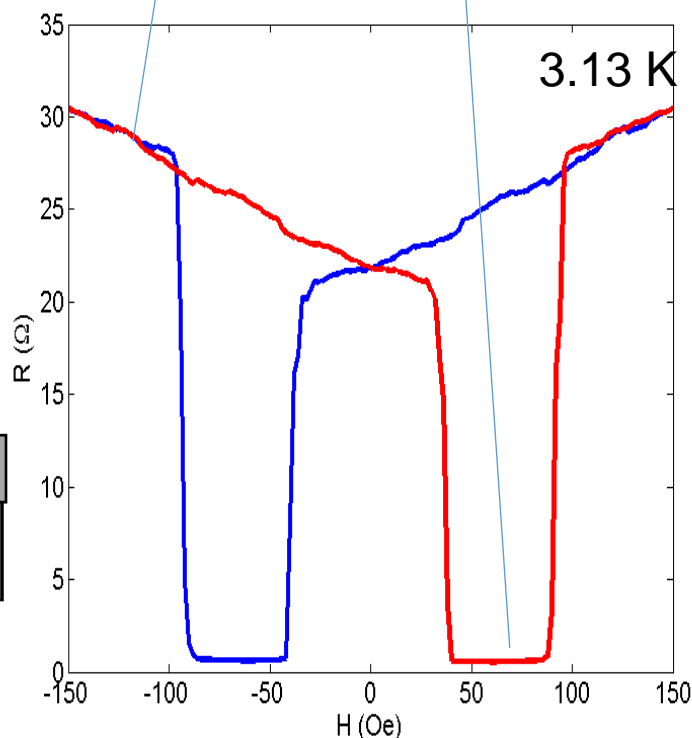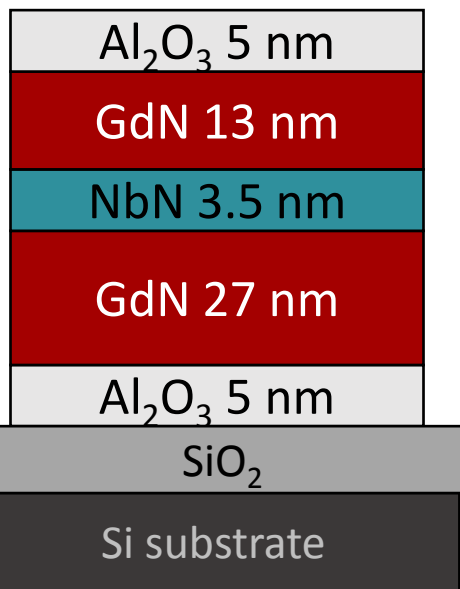
**SC Resistive transition**

3.13 K

**Perfect spin switching**
**Interface driven**

# Topological Insulators (TIs)



Topological Insulators

Conduction Band

+ Ferromagnetic order

Conduction Band

$E_F$

Valence Band

Valence Band
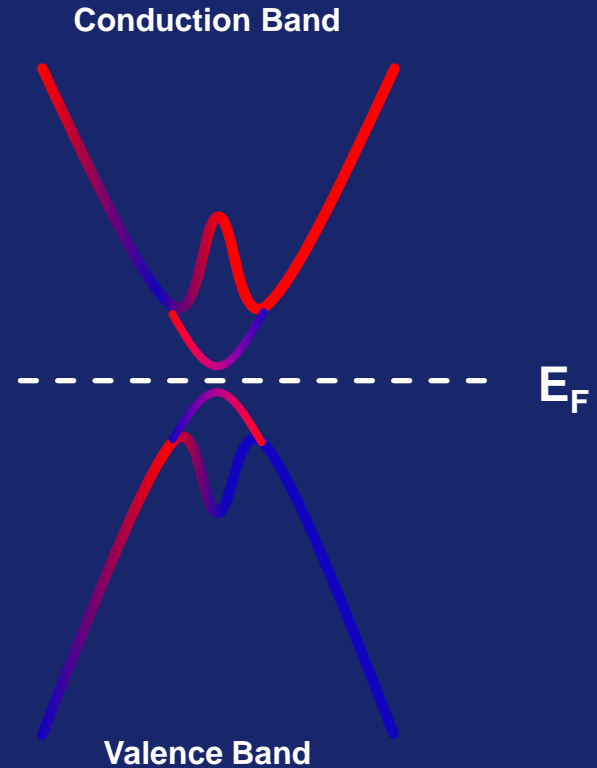
**Quantum anomalous Hall (QAH) effect**

# Quantum anomalous Hall (QAH) effect



**AHE** → **QAHE**

$\rho_{yx}$ ... $B$ ... $\dfrac{h}{e^2}$ ... $B$

**magnetic field**

$B$ ... $-e$ ... $-e$ ... $-e$ ... $-e$

Current
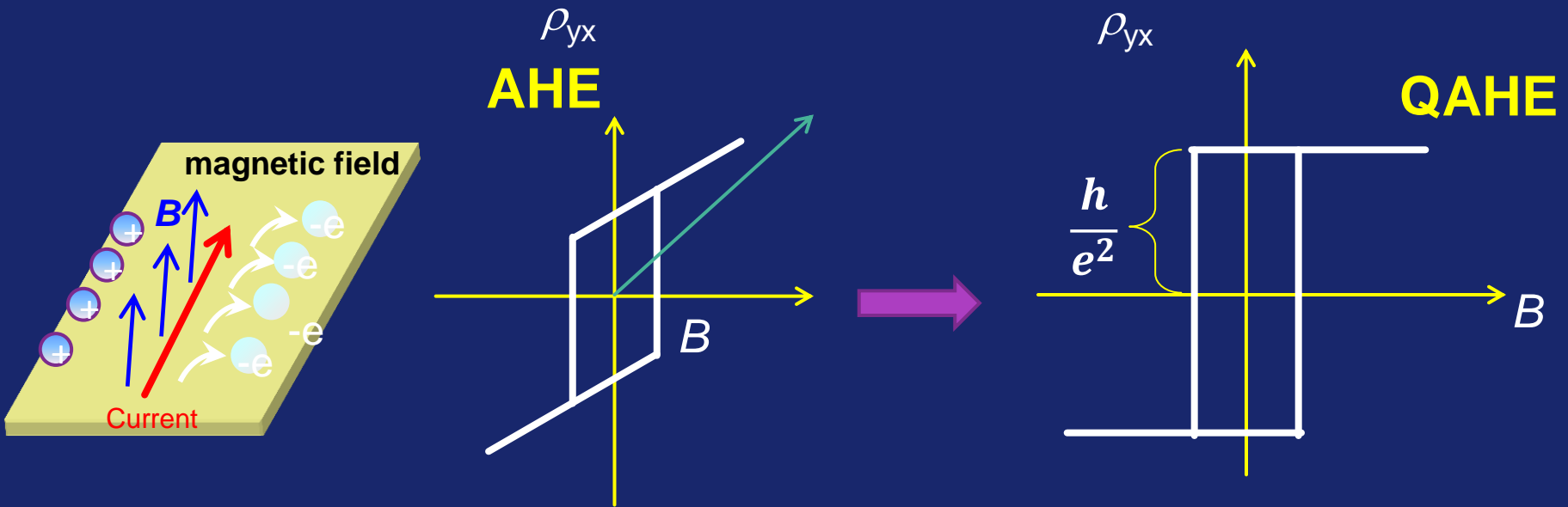
Hall effect at zero field
in a magnetic material

Quantum Hall effect at zero field

- Ferromagnetic insulator
- Topologically non-trivial electronic band structures

$$\rho_{yx} = \frac{h}{e^2} = 25.812 \, \text{K}\Omega$$

$$\rho_{xx} = 0$$

QAH insulator

Spin polarized ballistic chiral edge mode

- **TI thin films and heterostructures - High quality**

  → Homogeneous composition

  → Negligible defects
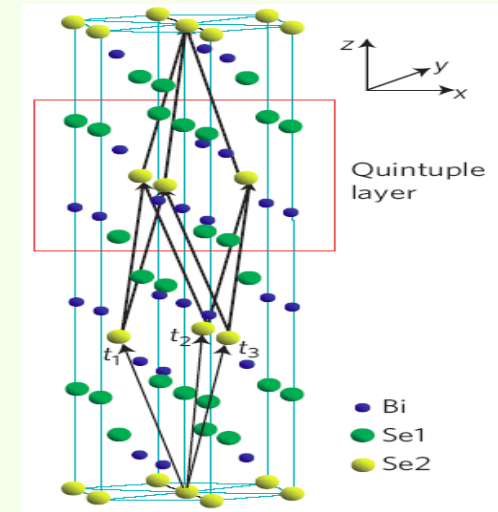
  → High mobility and low carr. density

**To reach QAH state**

- **Create ferromagnetic TI by doping**
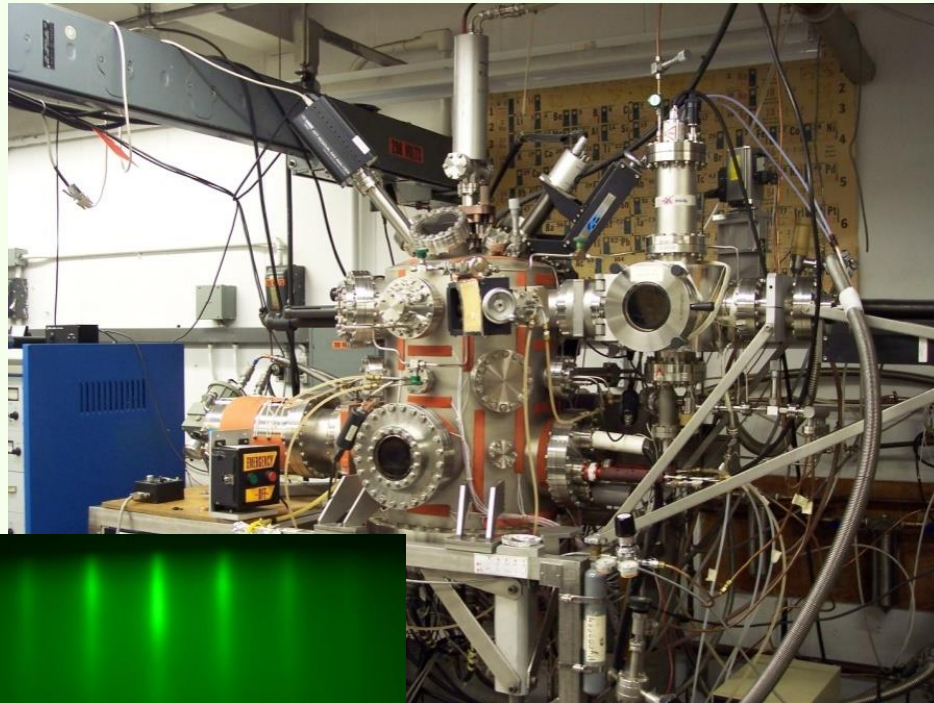  *– where does the dopant go?*

- **TI/FMI heterostructure**
  **Interface coupled magnetic behavior**
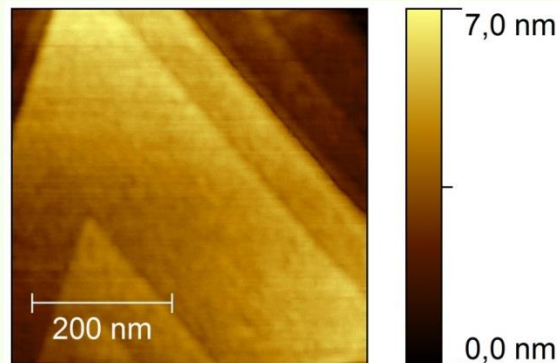
# Epitaxial growth (MBE) of TI layers

## $Bi_2Se_3$



Quintuple layer

- Bi
- Se1
- Se2

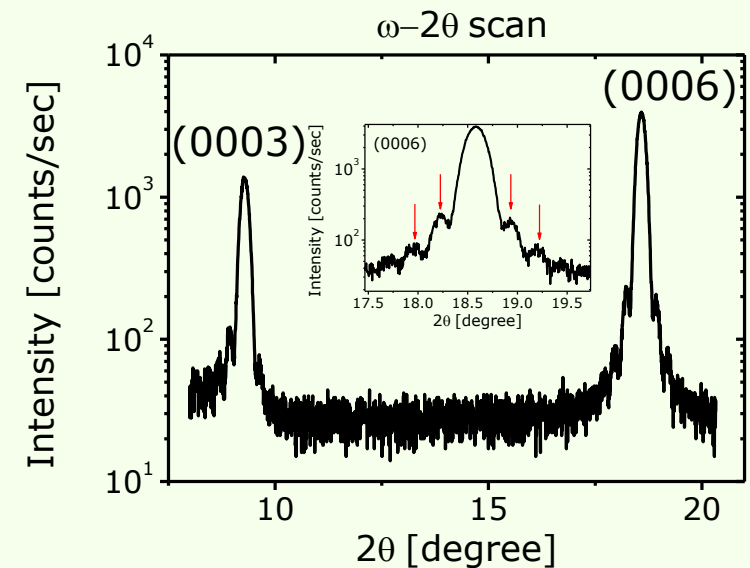H. Zhang et al Nat Phys 5, 438 (2009)

[1,-1,0,0] direction of c-cut sapphire

AFM image shows single quintuple layer steps

Layer by layer growth
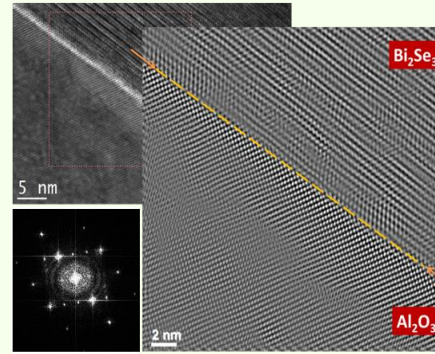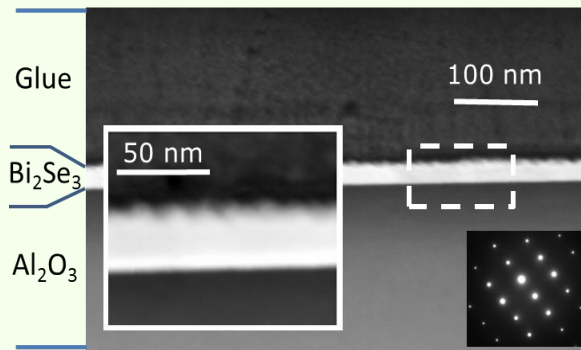Insitu capping

Heterostruc. possible
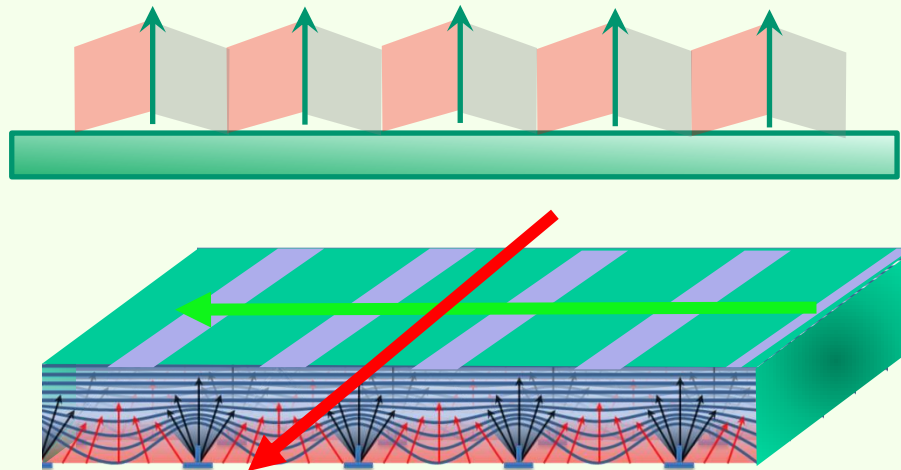 TI-I-Metal   TI-SC
        TI-FMI



7,0 nm

200 nm

0,0 nm

$\omega-2\theta$ scan



(0003)

(0006)

Intensity [counts/sec]

$2\theta$ [degree]

XRD shows single high crystalline quality and terraced surface

# - Dislocation mediated structural ordering -
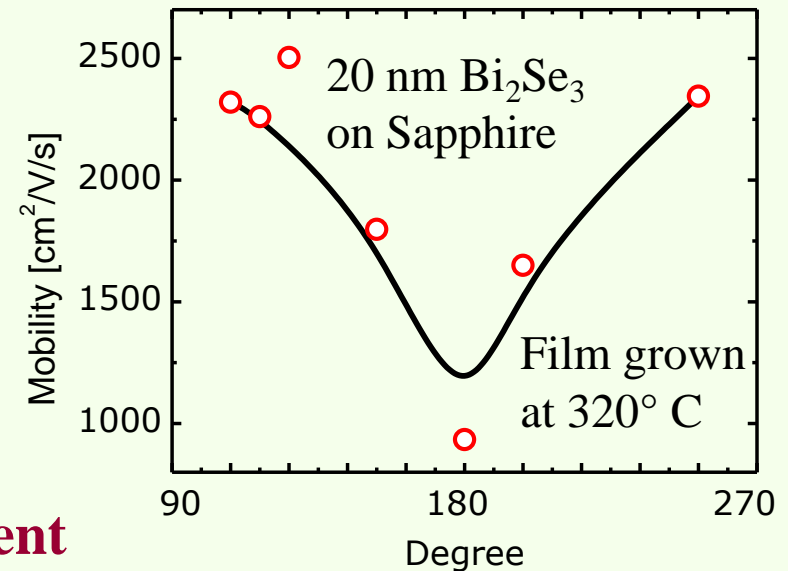# Signature of ordering, influence on carrier mobility



**Strong structural anisotropy!**
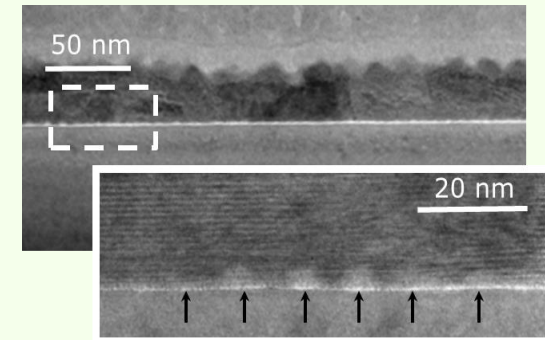
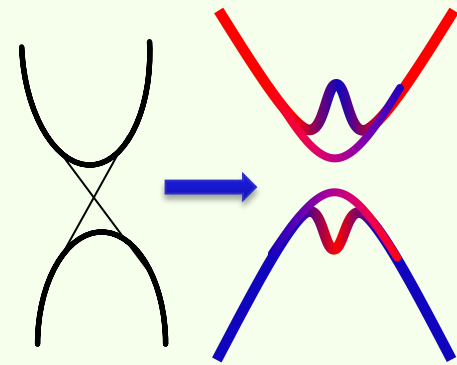**XTEM, STEM data very valuable**



**Mobility depends on the current direction w.r.t. dislocation lines !**

# *To observe QAH state*



## *Create a ferromagnetic TI*

*-  Surface Dirac cone opens up a gap ….*

**Control film thickness and carrier density to achieve QAHE**

**Doping TI with magnetic impurities: Cr,  Mn,  V *etc*.**

*Reduces surface mobility, spin disorder*
*Higher Tc requires high doping, lowering S-O - can destroys nontrivial surface states*
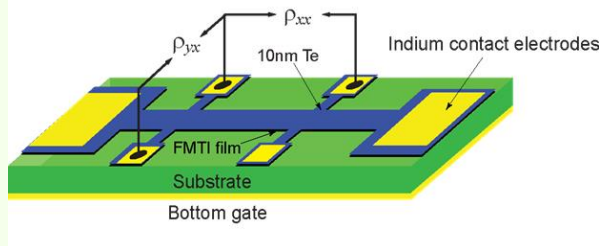
-    Proximity driven:  through internal exchange field with a magnetic insulator

Independent optimization of elec. and mag. properties

Could be a cleaner approach!

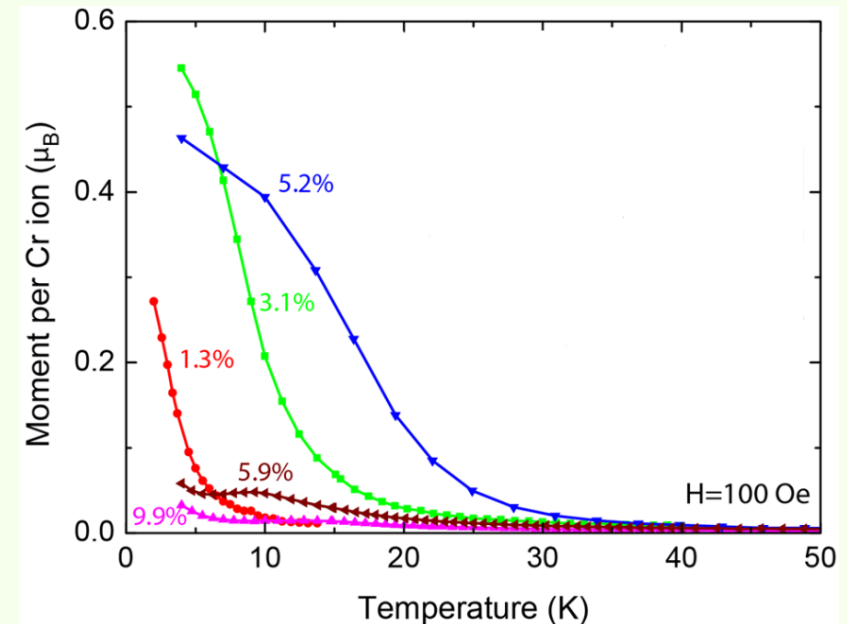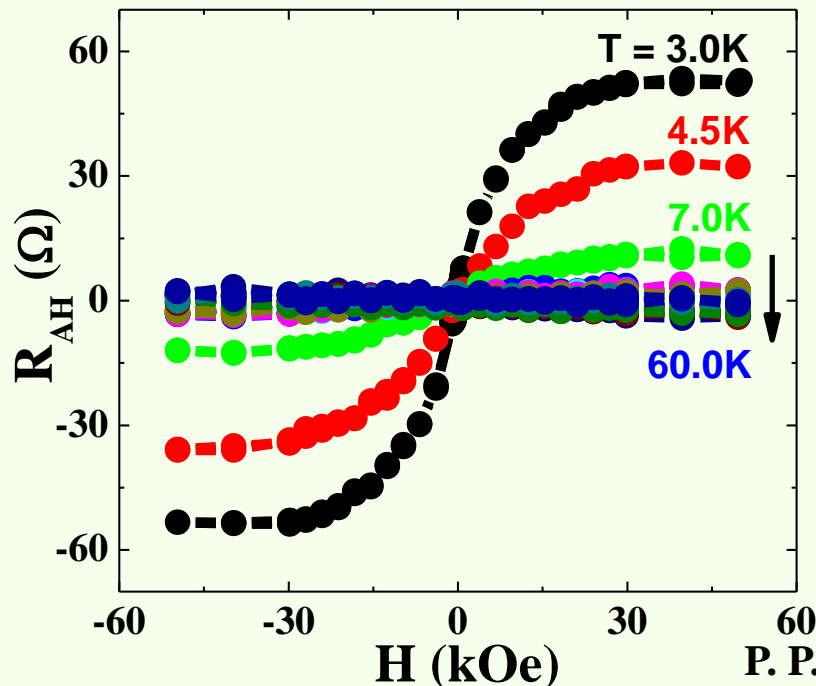# Ferromagnetism in Cr-doped $Bi_2Se_3$ epitaxial films (2010-11)

- Lattice parameter c increased (~0.2 %)
- Strain increased
- With increasing Cr concentration  crystal/film quality decreased



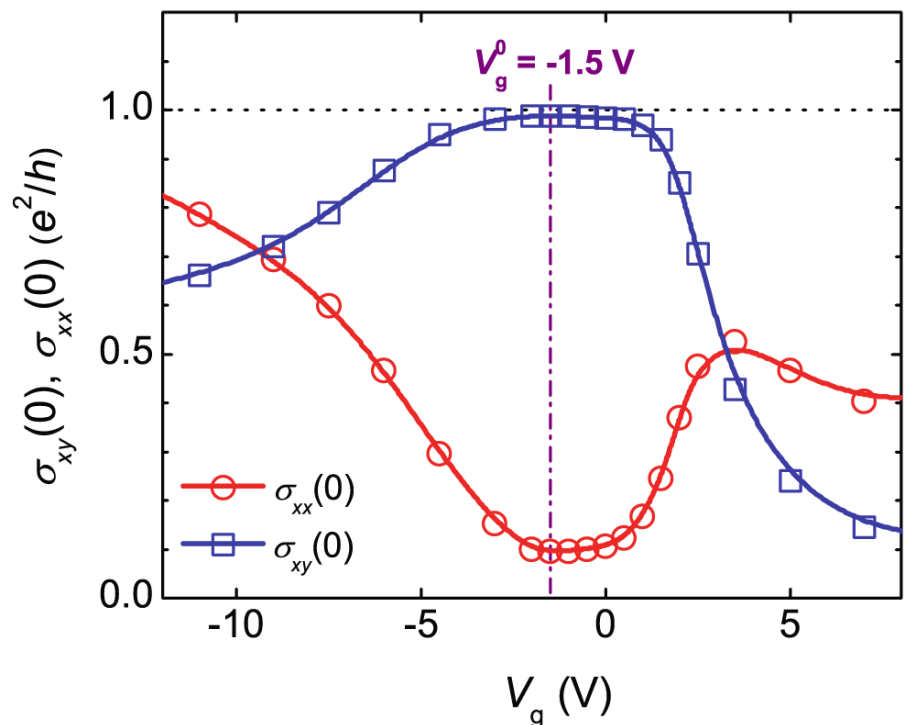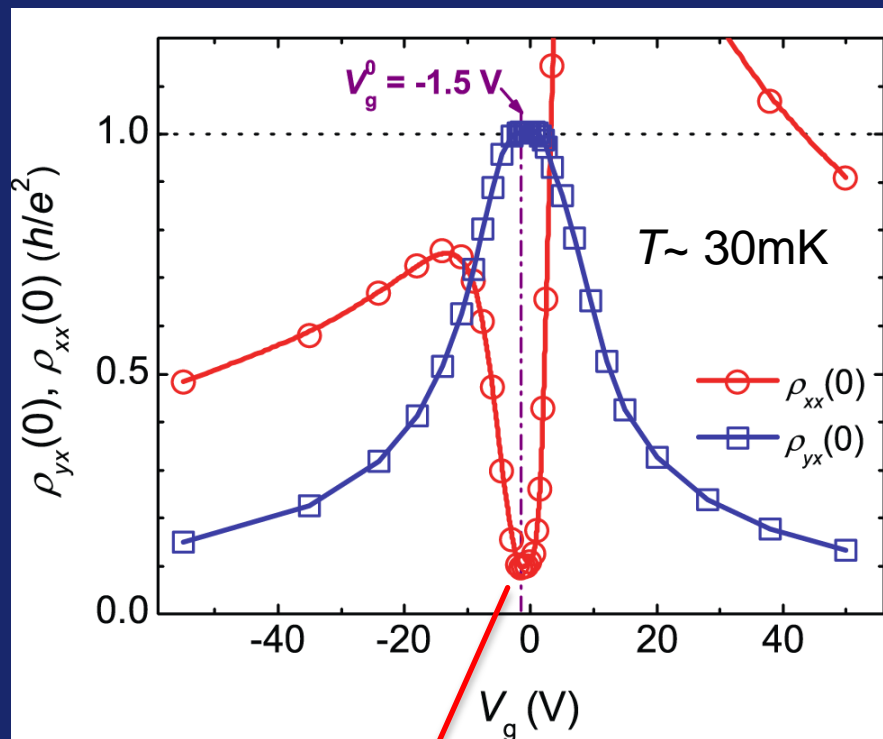**Film quality optimized: 5%  Cr**

**Tc dependence on  Cr content**

**Anomalous Hall effect seen**





P. P. J. Haazen,  J. B. Laloe, P. Wei.... JSM,  (2010,  APL 2012)

# QAHE in 5QL Cr-doped $(Bi_{0.1}Sb_{0.9})_2Te_3$ film - ferromagnetic TI



$V_g^0 = -1.5$ V

$\rho_{yx}(0)$, $\rho_{xx}(0)$ ($h/e^2$)

$T \sim 30$mK

$\rho_{xx}(0)$
$\rho_{yx}(0)$

$V_g$ (V)

$\sigma_{xy}(0)$, $\sigma_{xx}(0)$ ($e^2/h$)

$V_g^0 = -1.5$ V

$\sigma_{xx}(0)$
$\sigma_{xy}(0)$

$V_g$ (V)

Not completely dissipationless

$$\rho_{xx} \sim 2.53 K\Omega$$
$$\rho_{yx} = 1\frac{h}{e^2}$$

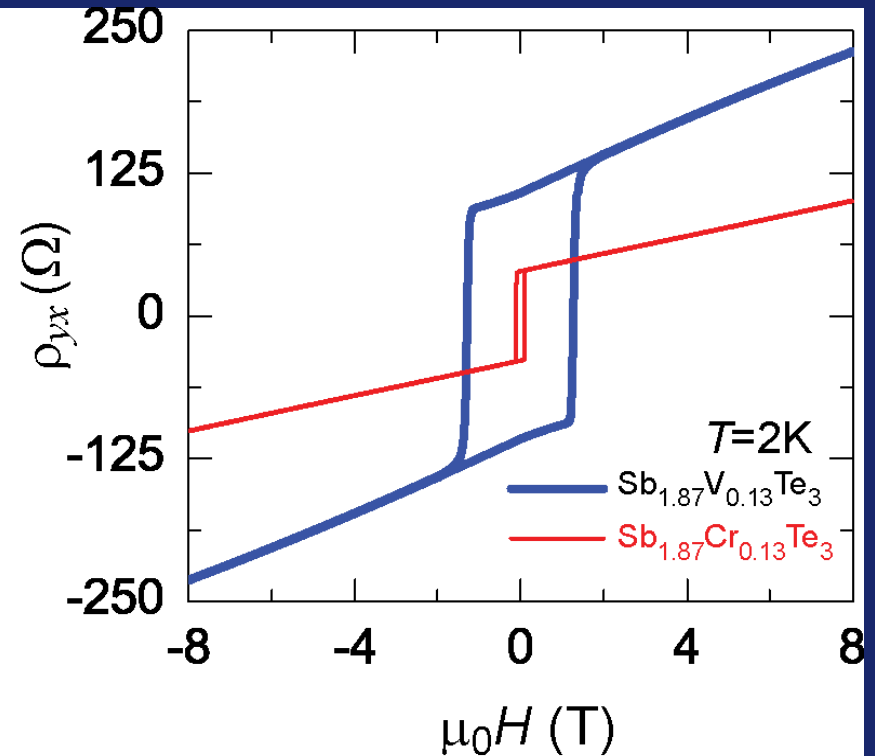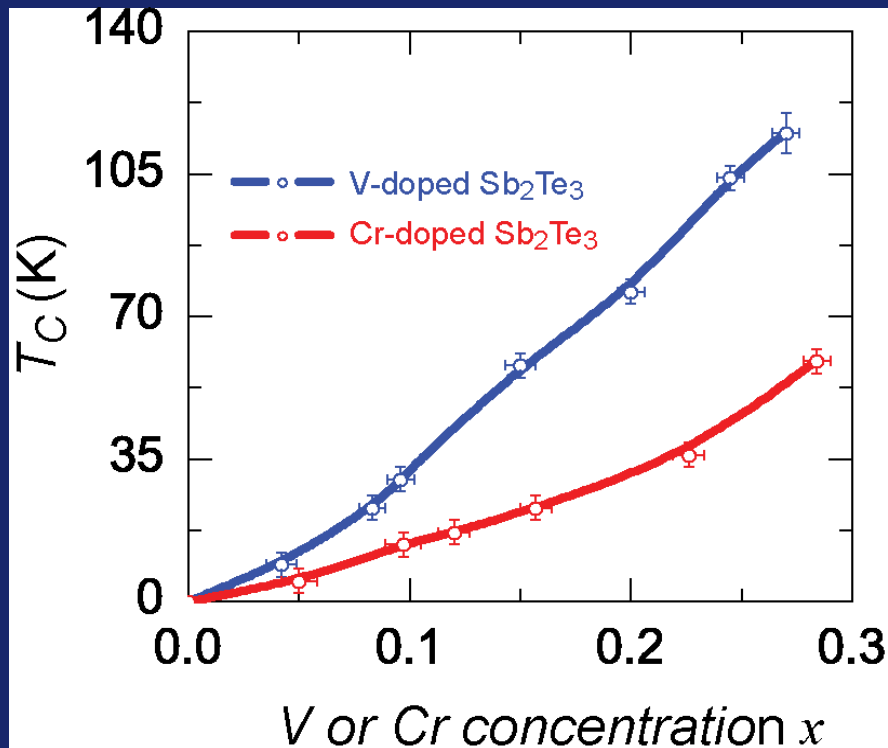$$\sigma_{yx} \sim 0.99 \frac{e^2}{h}$$

$$\tan\alpha = \frac{\rho_{yx}}{\rho_{xx}} \sim 11$$

Chang *et al. Science* **340**,167 (2013).

# Ferromagnetic properties
# Comparing Cr- and V-doped $Sb_2Te_3$ films
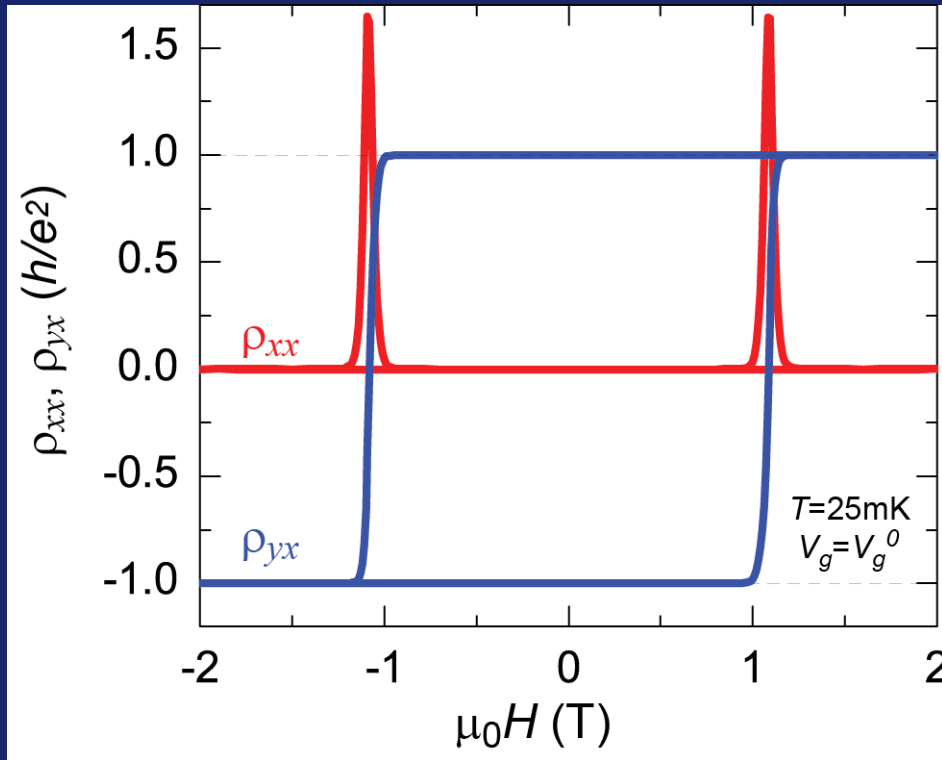
## 6 QL $Sb_{2-x}V_xTe_3$ and $Sb_{2-x}Cr_xTe_3$



## $Sb_{2-x}V_xTe_3$ : Higher Curie temp.

## Giant coercive field

- Magnetic moment per V ion 1.5 $\mu_B$ for x = 0.13
  - valence state of V is a mixture of 3+ and 4+ (or/and 5+)
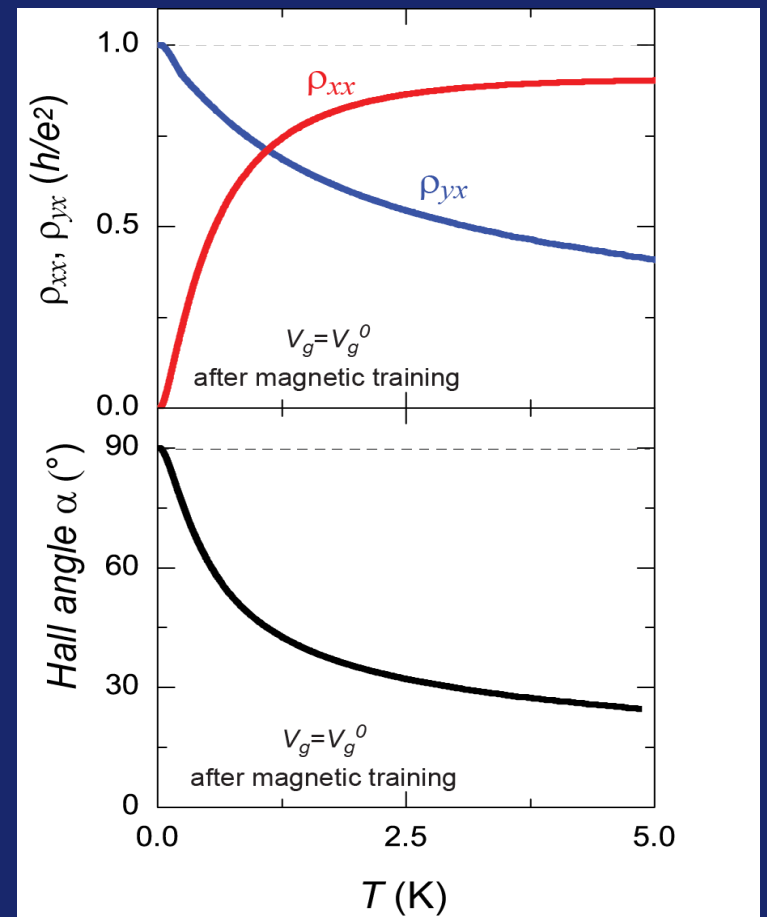    - reduces *p*-type carriers by *n*- doping

# High-precision QAHE



At H = 0

$\rho_{yx}$=1.00019±0.00069 $h/e^2$
$\rho_{xx}$= 0.00013±0.00007 $h/e^2$ (~3.35±1.76$\Omega$)

$\rho_{yx}(0)/\rho_{xx}(0)$ ~ 7700    $\alpha$ ~ 89.993±0.004º

$$\rho_{yx} = \frac{h}{e^2} = 25.812 \text{ K}\Omega$$

$$\rho_{xx} = 0$$
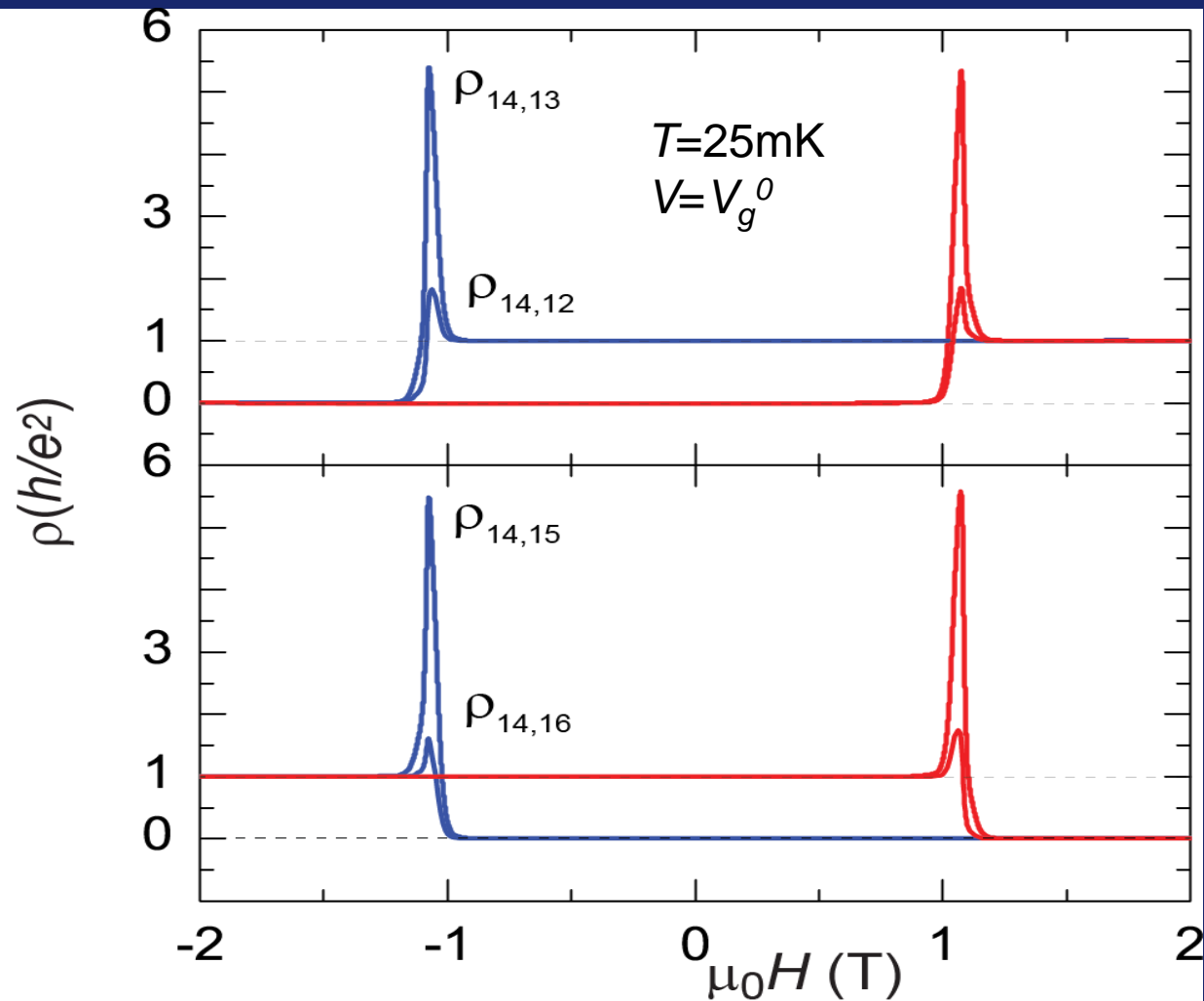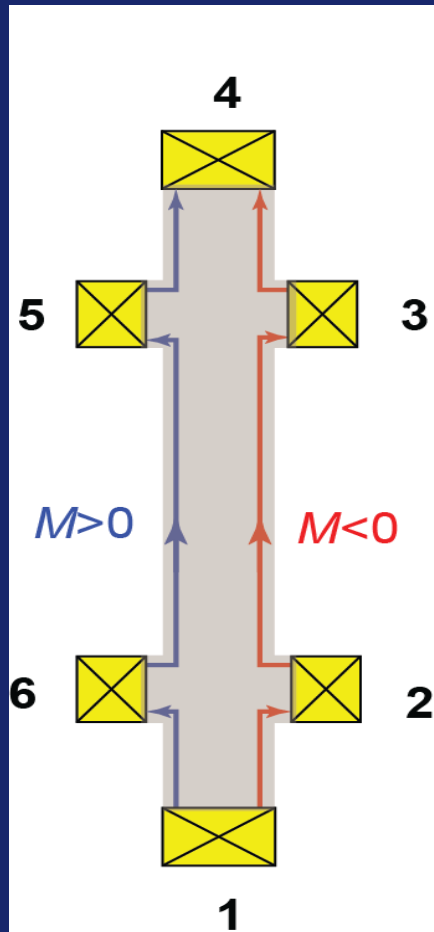
QAH state up to ~5K

# Chiral edge dissipationless transport

4QL $V_{0.11}(Bi_{0.32}Sb_{0.68})_{1.89}Te_3$
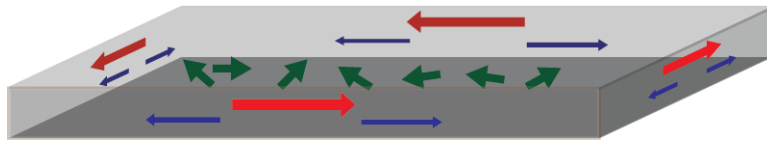
Asymmetric loops
Mirror symmetric behavior of $\rho_{14,16}$ ($\rho_{14,15}$) and $\rho_{14,12}$ ($\rho_{14,13}$)
The chirality of edge transport in QAH state

PRL (2015)

# Complex - several conducting channels
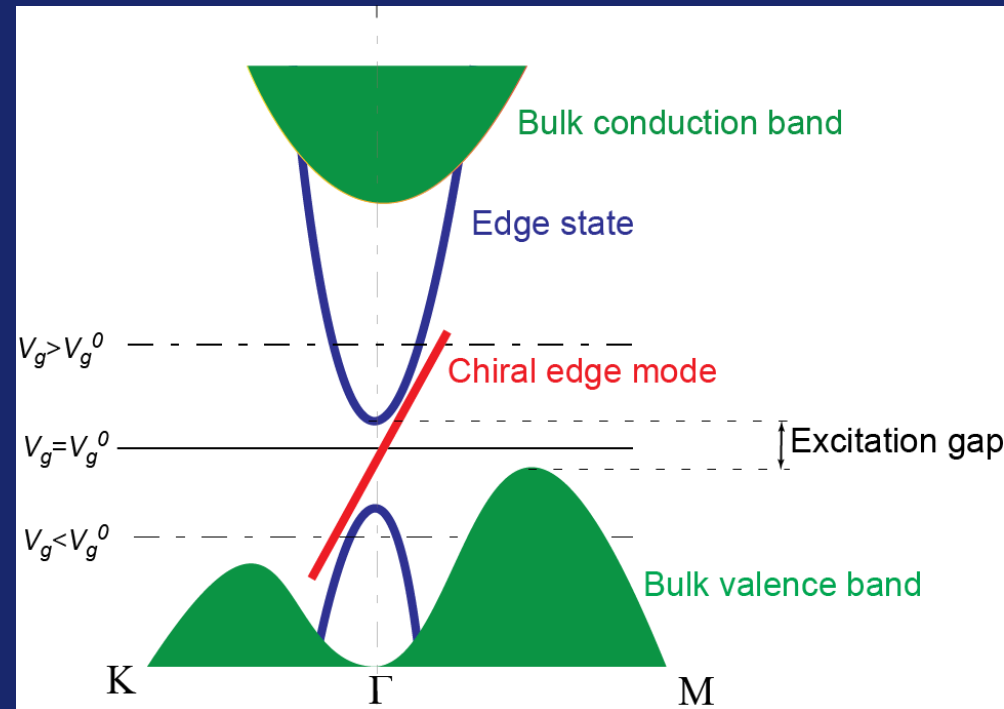


Red: Chiral edge mode

Blue: Nonchiral edge mode

Green: Bulk channels

Non-uniform exchange gap

Activation energy ~ 100 $\mu e$V

$V_g = V_g^0$

Chiral edge channel (red) (dissipationless)

$V_g > V_g^0$

Nonchiral edge channel (blue) (dissipative) + Chiral edge channel (red) (dissipationless)

$V_g < V_g^0$

Bulk channels (green) (dissipative) + Chiral edge channels (red) (dissipationless)

# Creating ferromagnetic state by proximity coupled interfacial exchange field



**Very effective with superconductors**
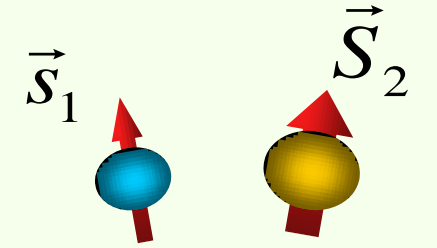
PRL 1986, 1988, 1991, 1993, 2007, 2008, 2009;

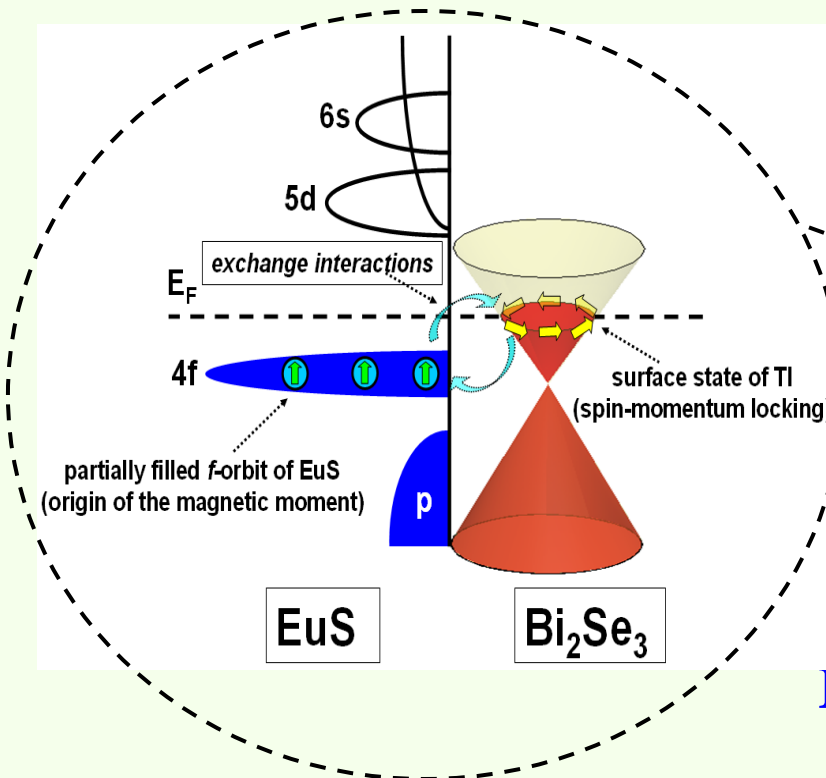Nat. Commun. 2014;  PCCP 2015

Nature 2016, Nature Matl. 2016

# *Internal exchange field:* Proximity induced surface ferromagnetism in TI

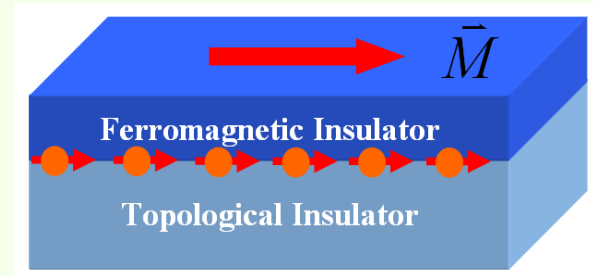## Large internal exch. field at FI/TI interface
## > many Tesla

- **Ferromagnetic Insulators (FI): EuS, Eu$^{2+}$ ion: 7 $\mu_B$**

- *4f-5d* **energy gap: 1.64 eV (EuS) or 1.12 eV (EuO)**
- **Exchange interaction energy J ~ 15 meV**

$$H_{ex} = -J \, \vec{s}_1 \cdot \vec{S}_2$$

**de Gennes 1966**
**Sarma 1963**

*FI/TI (bi-layer)*

6s

5d

exchange interactions

$E_F$

4f

surface state of TI
(spin-momentum locking)

partially filled *f*-orbit of EuS
(origin of the magnetic moment)

p

EuS    Bi$_2$Se$_3$

$\vec{M}$

**Ferromagnetic Insulator**
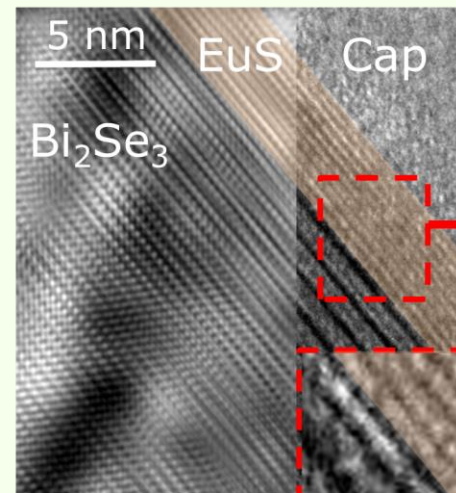
**Topological Insulator**

**Split surface bands**
**(short range interaction)**

**Ideal for TI as interaction is at the surface**

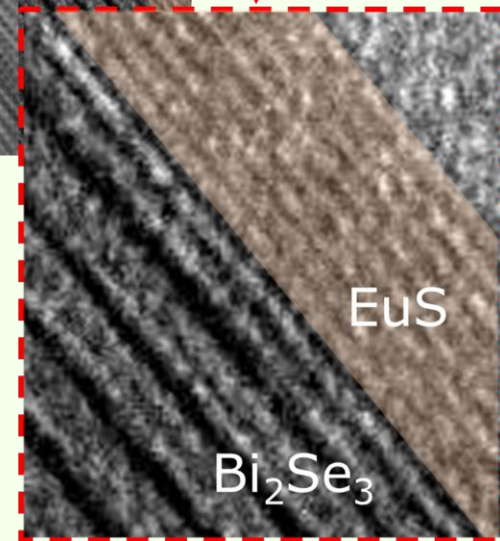# Introducing ferromagnetism on TI surface via interfacial exchange fields
## Ferromagnetic Insulator / TI



**Epitaxial bilayer of Bi$_2$Se$_3$ / EuS**
*XTEM studies*

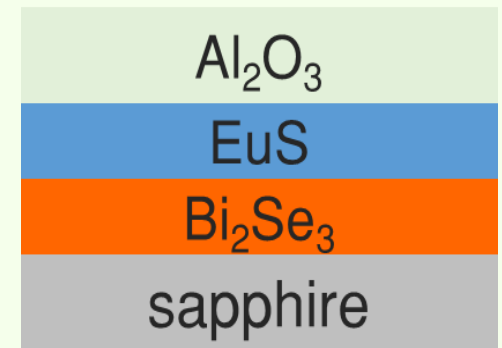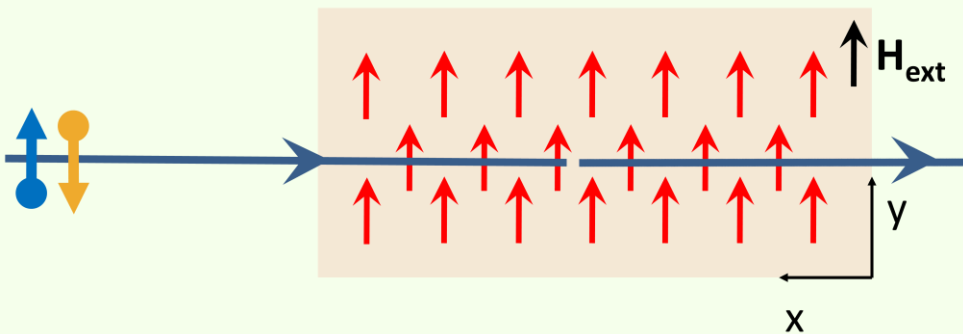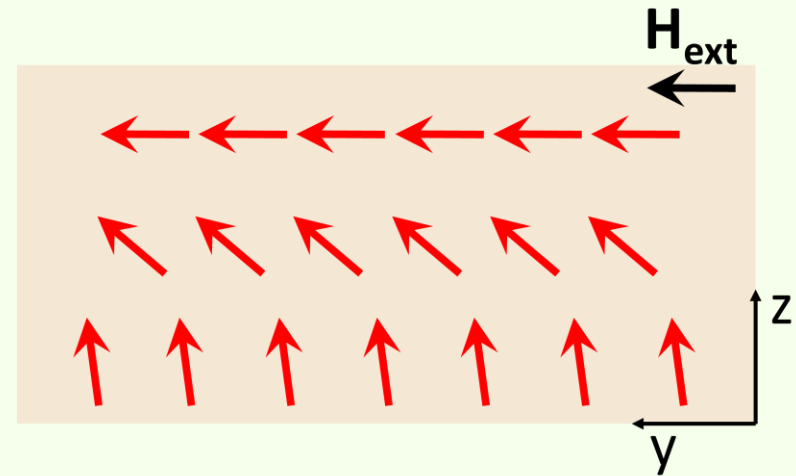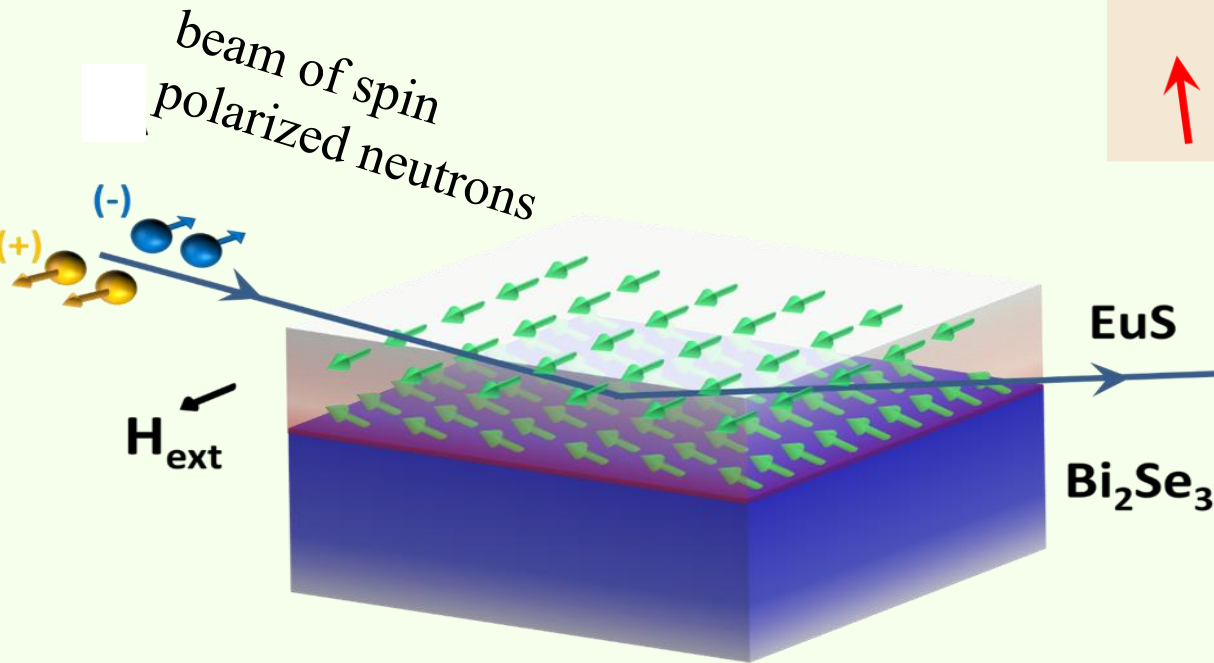Independent optimization of elec. and mag. properties

Could be a cleaner approach!

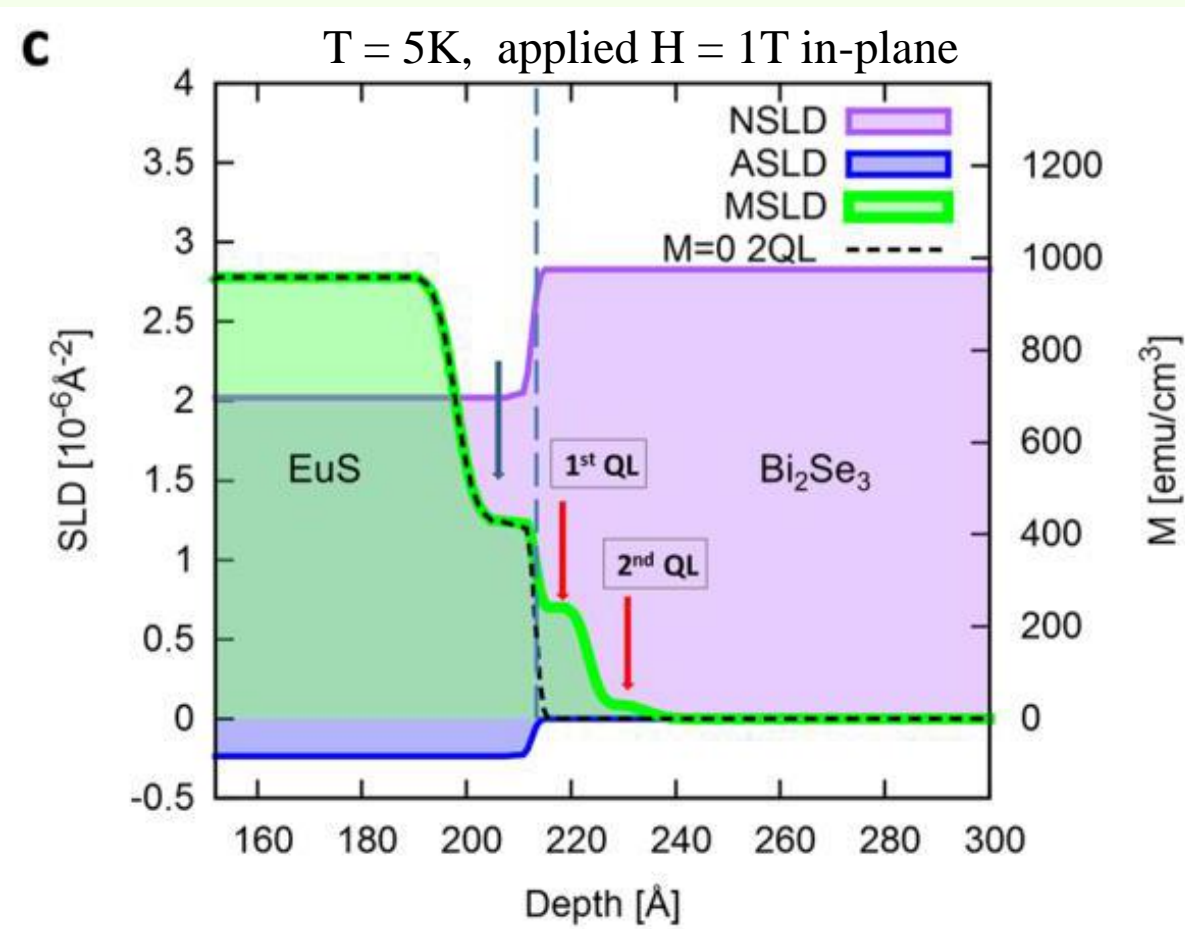# Polarized Neutron Reflectometer
Oakridge Nat. Lab (Valeria Lauter)

**Probing the interface spins**

$H_{ext}$

beam of spin
polarized neutrons

(−)

(+)

EuS

$H_{ext}$

$Bi_2Se_3$

z

y

$H_{ext}$

y

x

$Al_2O_3$

EuS

$Bi_2Se_3$

sapphire

# Interface layer ferromagnetism in TI
## by Spin-Polarized Neutron Reflectivity

**PNR signal showing induced M in EuS/$Bi_2Se_3$**



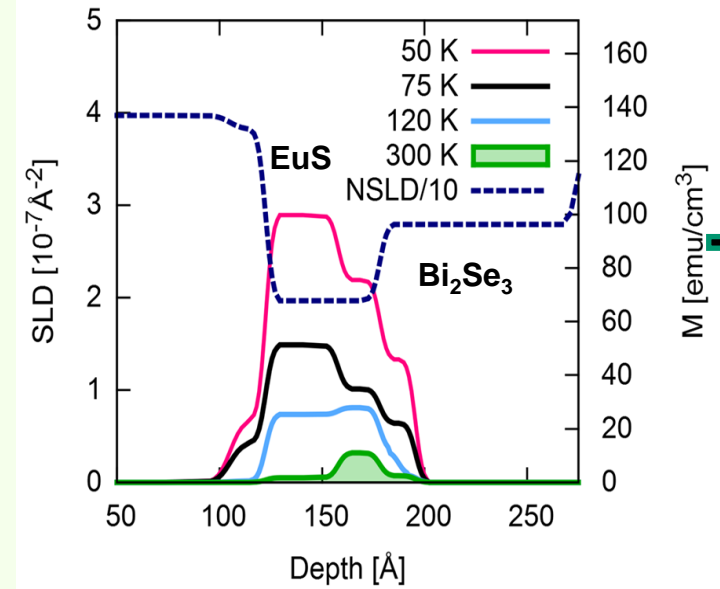T = 5K, applied H = 1T in-plane

**Depth profile of the interface magnetization**



F. Katmis …. JSM, Nature, 2016
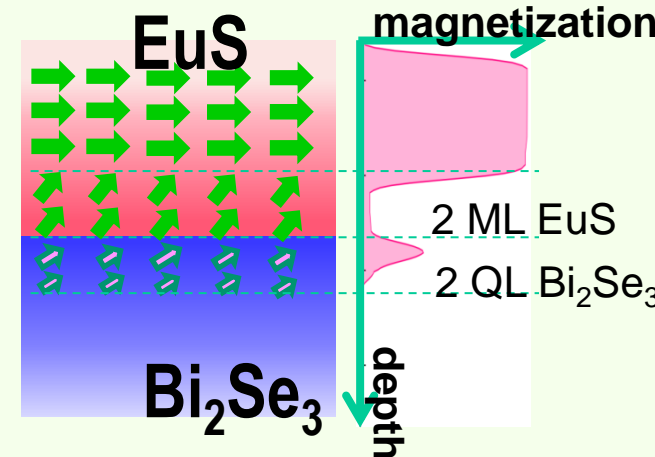
# Polarized Neutron Reflectometer: $Bi_2Se_3$/EuS (10 QL / 5 nm)
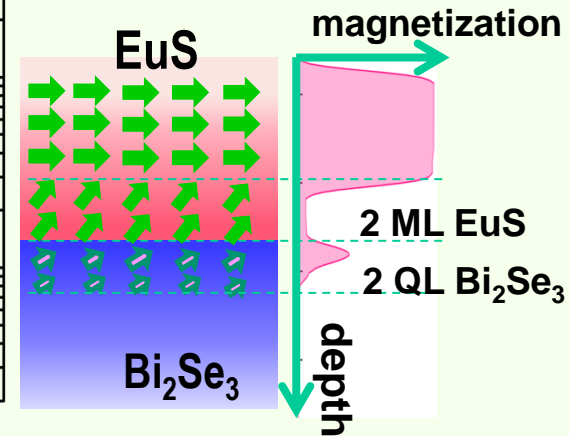
**Depth profiles at different temp.**
$H_{appl}$ = 1T *in plane*

M vs T of $Bi_2Se_3$ from PNR data
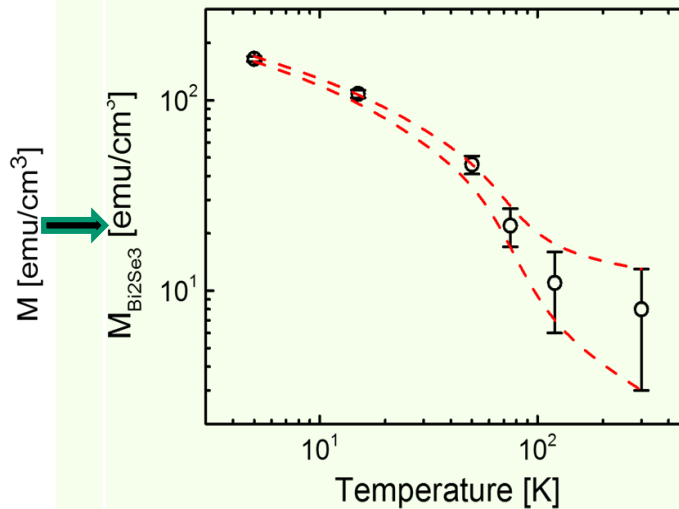
**Depth profile of interface magnetization**



**Katmis et al Nature, 2016**

- High quality thick EuS layer magnetization confirmed by PNR (~7$m_B$ per $Eu^{2+}$ ion)

- **Canted interface EuS moment (planar ~ 0.3$m_B$/$Eu^{2+}$, corresponds to ~ 85° canting angle)**

- **Onset of large induced moment within the top 1-2 QL $Bi_2Se_3$, decays with depth**

- No induced interface moment seen in control sample of EuS/sapphire

# SQUID MAGNETOMETRY MEASUREMENT

## Magnetization vs. Temp. at various perpendicular applied fields
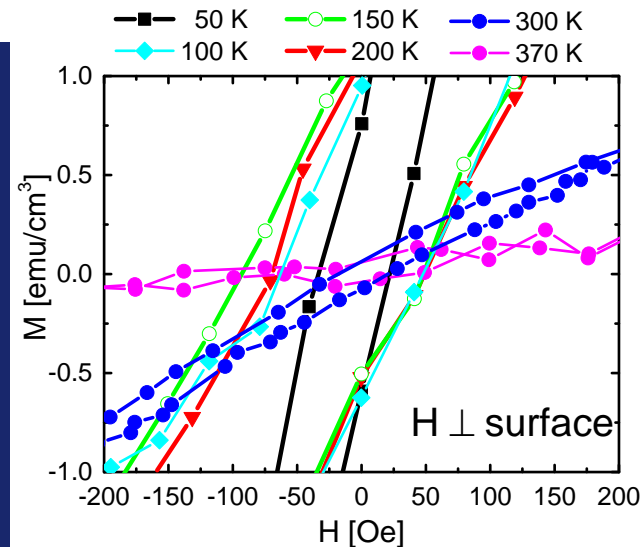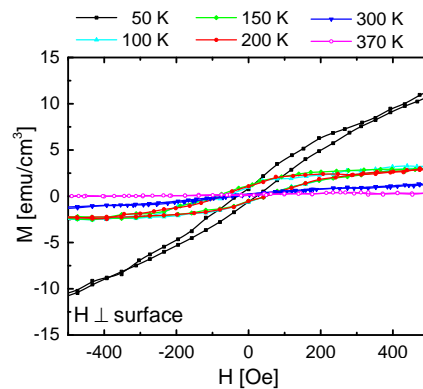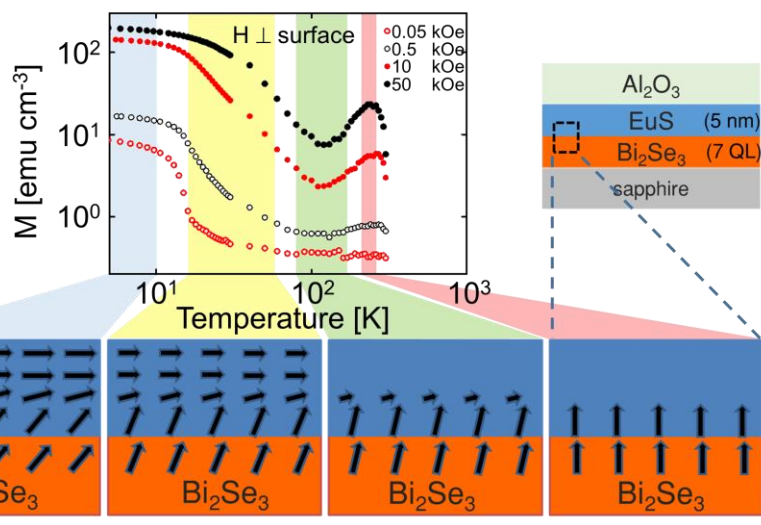


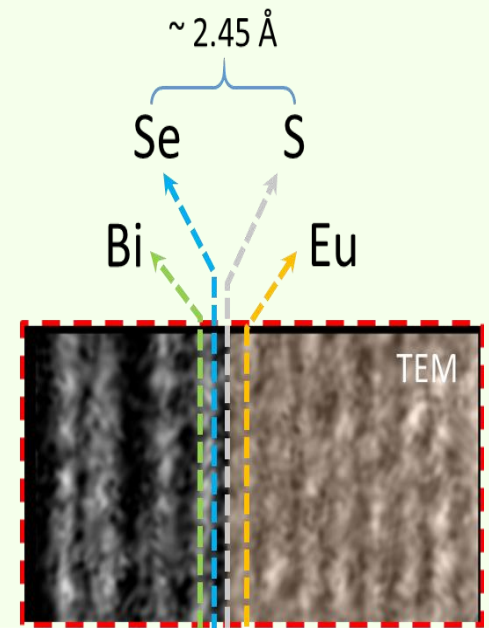**Magnetic hysteresis observed at all T**
**In agreement with PNR results**
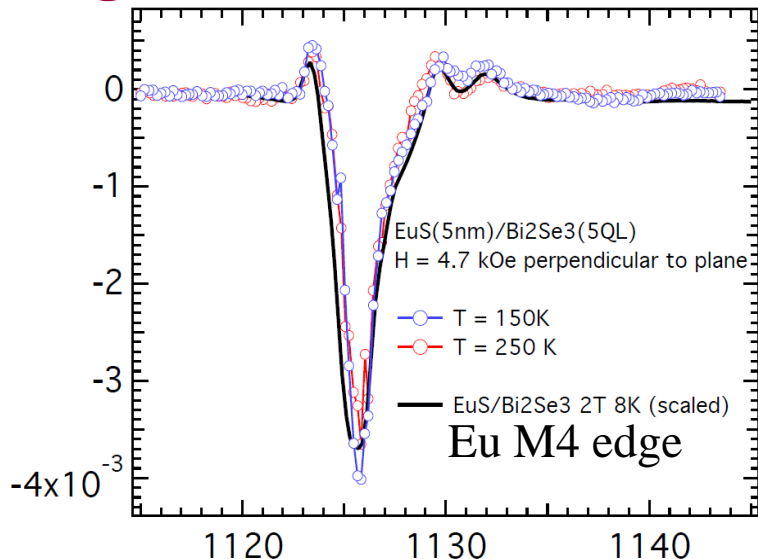
**At the interface**

- **Large S-O interaction, the spin-momentum locking at Dirac surface state creates strong anisotropy and stabilizes the ferromagnetic state?!**

# Electron density profile of EuS/Bi$_2$Se$_3$ bilayer
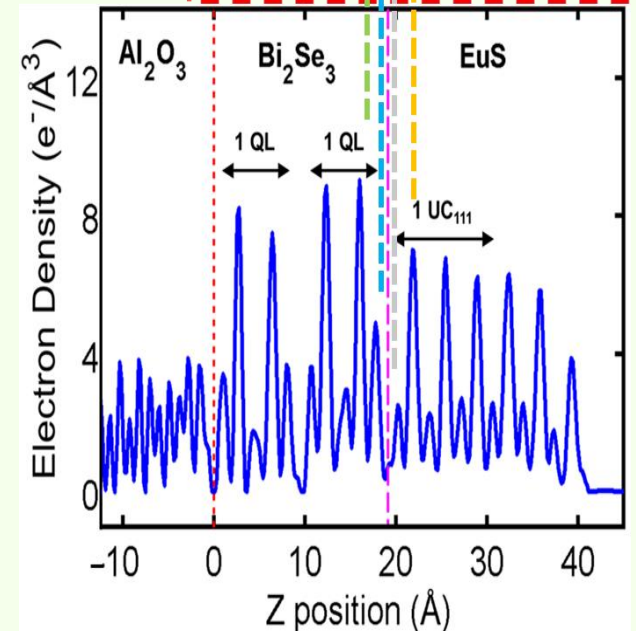## (glancing angle XRD analysis, synchrotron source used)

- **Bi$_2$Se$_3$ is terminated with Se layer at the interface; S layer is in direct stacking with Se layer**

- **Agrees with TEM analysis**

- **Sharp interface, no intermixing or inter diffusion**

- **Weak interfacial bonding van der Waals bond (~ 2.45 Å)**

## Magnetic circular dichroism vs. Temp.

EuS(5nm)/Bi2Se3(5QL)
H = 4.7 kOe perpendicular to plane

- T = 150K
- T = 250 K

EuS/Bi2Se3 2T 8K (scaled)

Eu M4 edge

**~ 0.05 - 0.1 uB per atom at 250K**
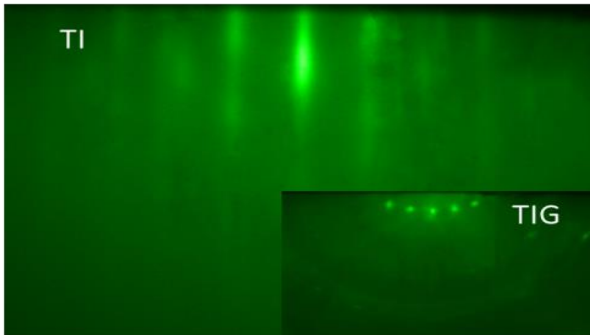
**EuS/Bi$_2$Se$_3$ interface layer shows ferromag. behavior at 250K >> T$_C$ (EuS)**
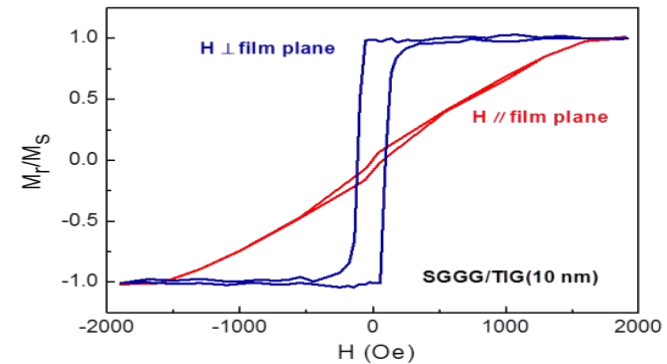
# …. *Going to higher temperature ….*
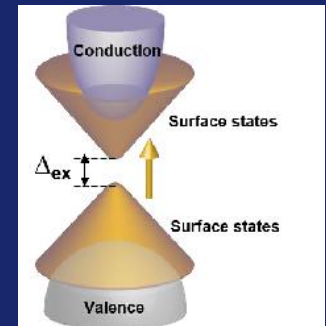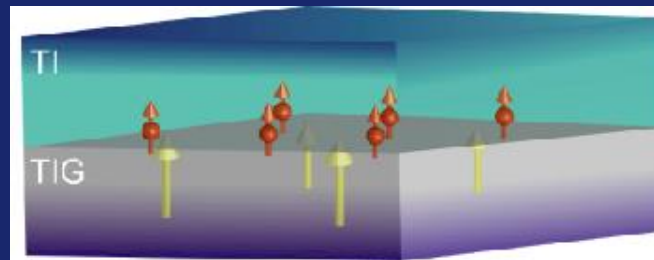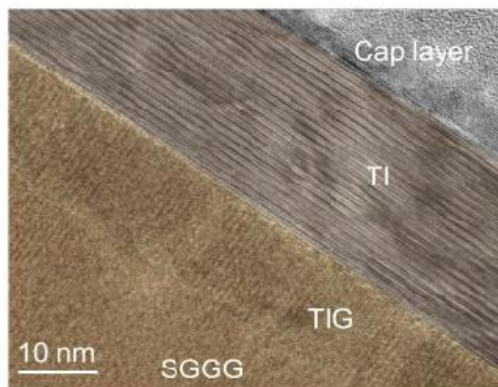## TI/TIG heterostructure *(Collab: Jing Shi, UC Riverside)*

RHEED patterns of TI/TIG

M-H loop of TIG substrate



TEM image of TI/TIG



$T_c \sim$560K ➡ Large exchange-induced gap

**Science Advances (Online June 2017)**
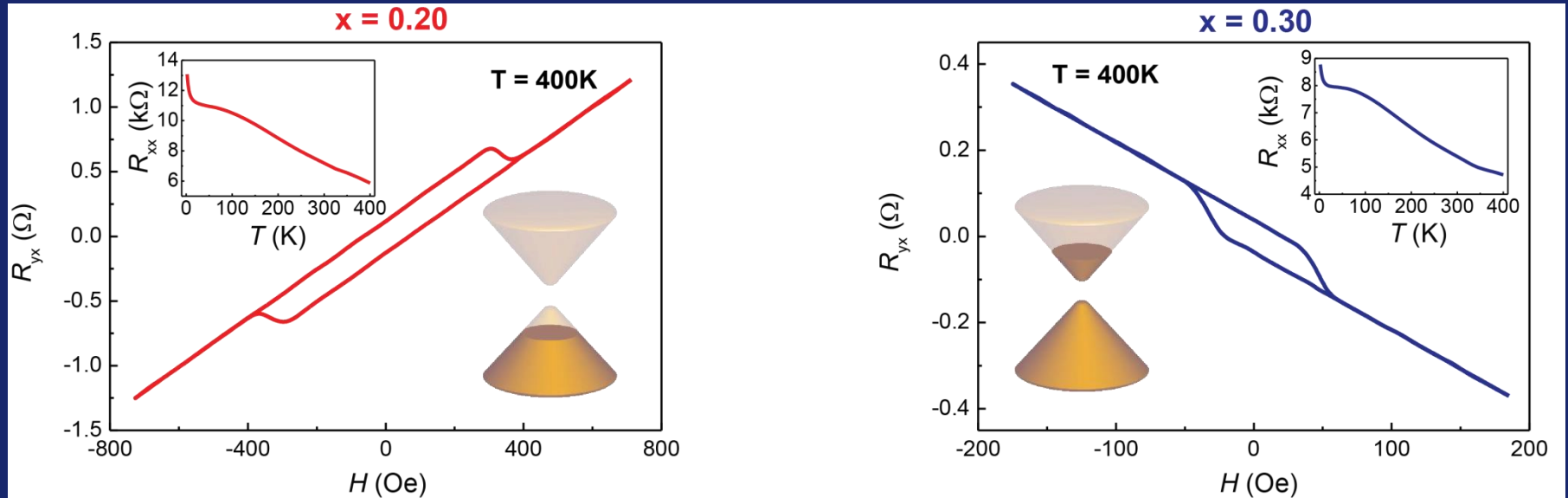
# Hall traces of TI/TIG heterostructure

**5QL $(Bi_xSb_{1-x})_2Te_3$**

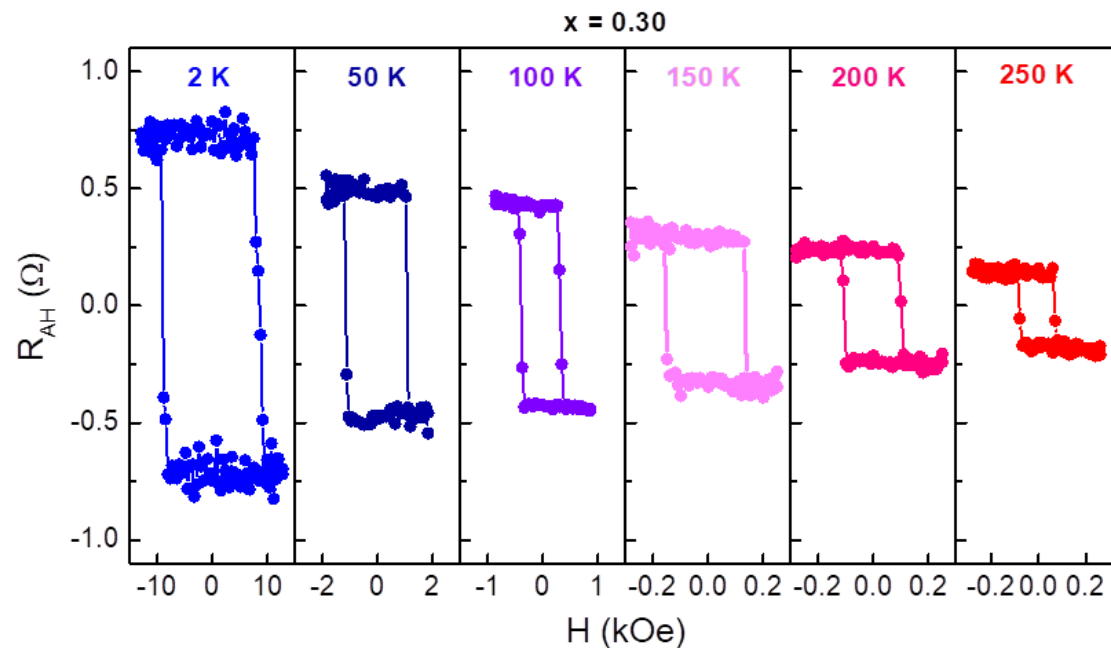*p*-type                                         *n*-type



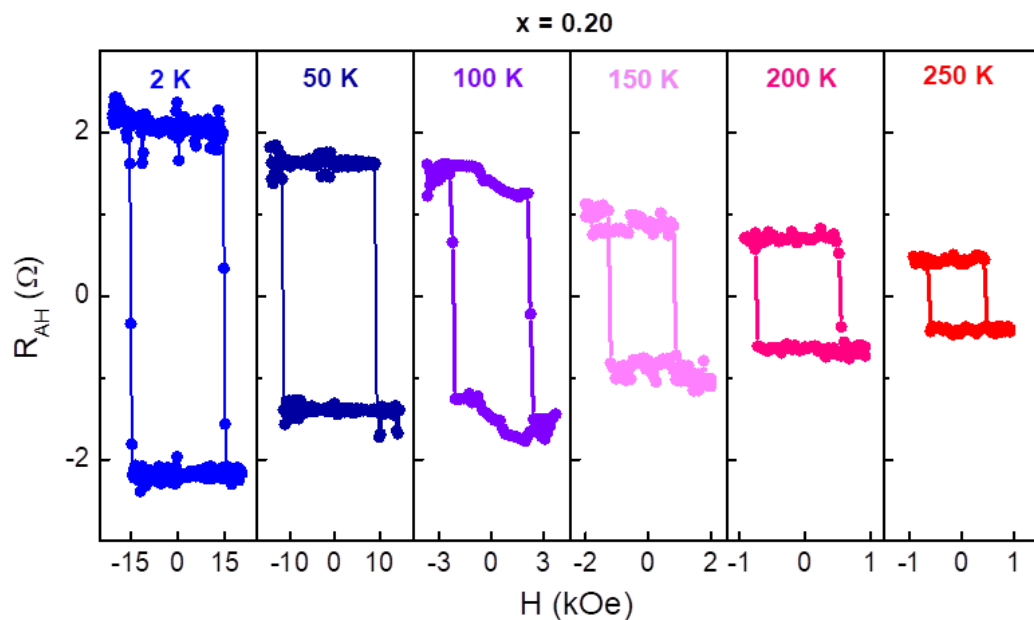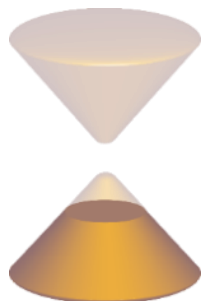The AHE loops have the same sign in these two samples despite the different carrier types

**NOT** Lorentz force-induced responses arising either from TIG stray fields or contributions from two types of carriers in TI

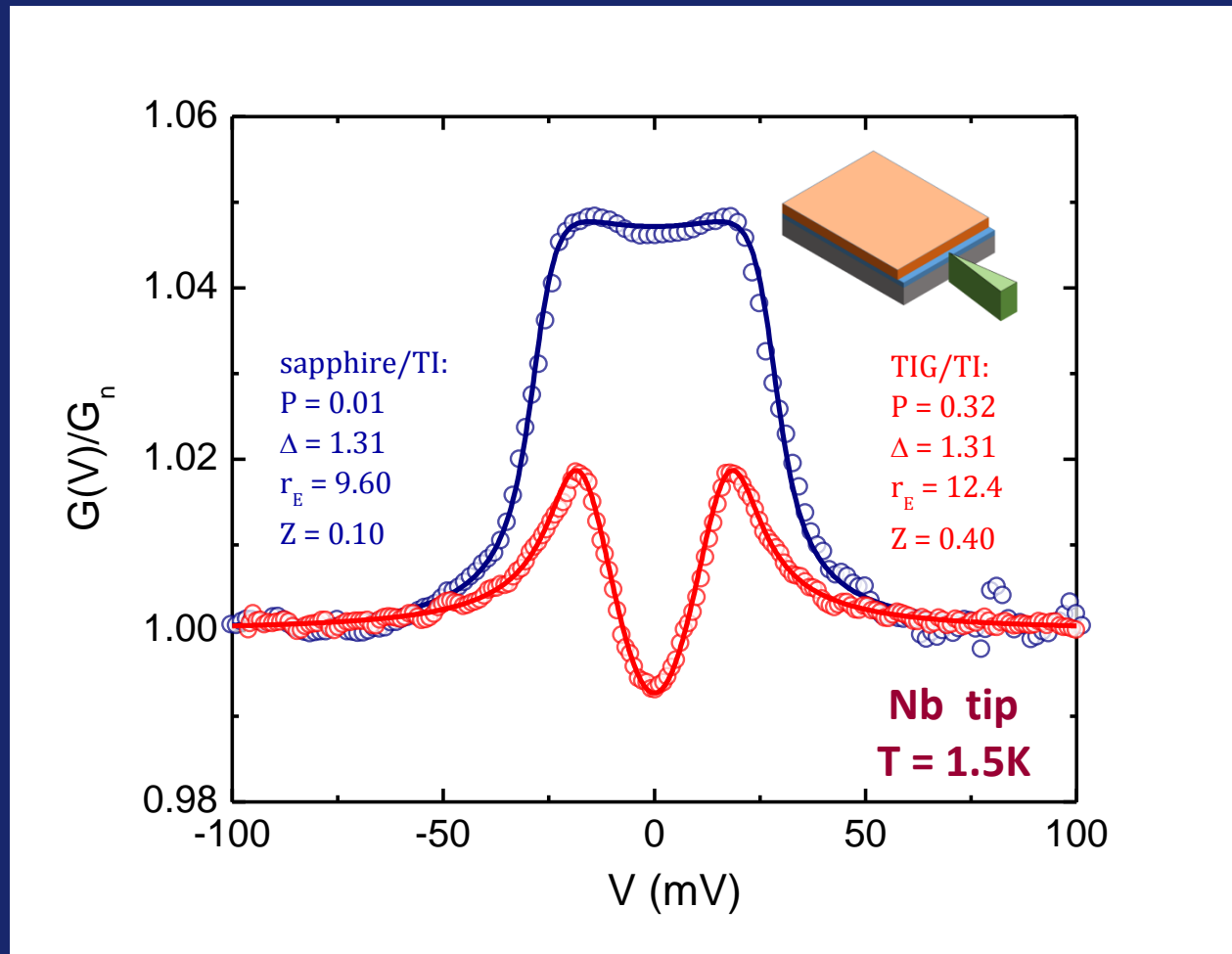# Anomalous Hall resistance in proximity coupled TIG/ 5QL TI



TIG/$(Bi_{0.3}Sb_{0.7})_2Te_3$

TIG/$(Bi_{0.2}Sb_{0.8})_2Te_3$

# Point-contact Andreev reflection spectroscopy (PCAR) on TI/TIG heterostructure
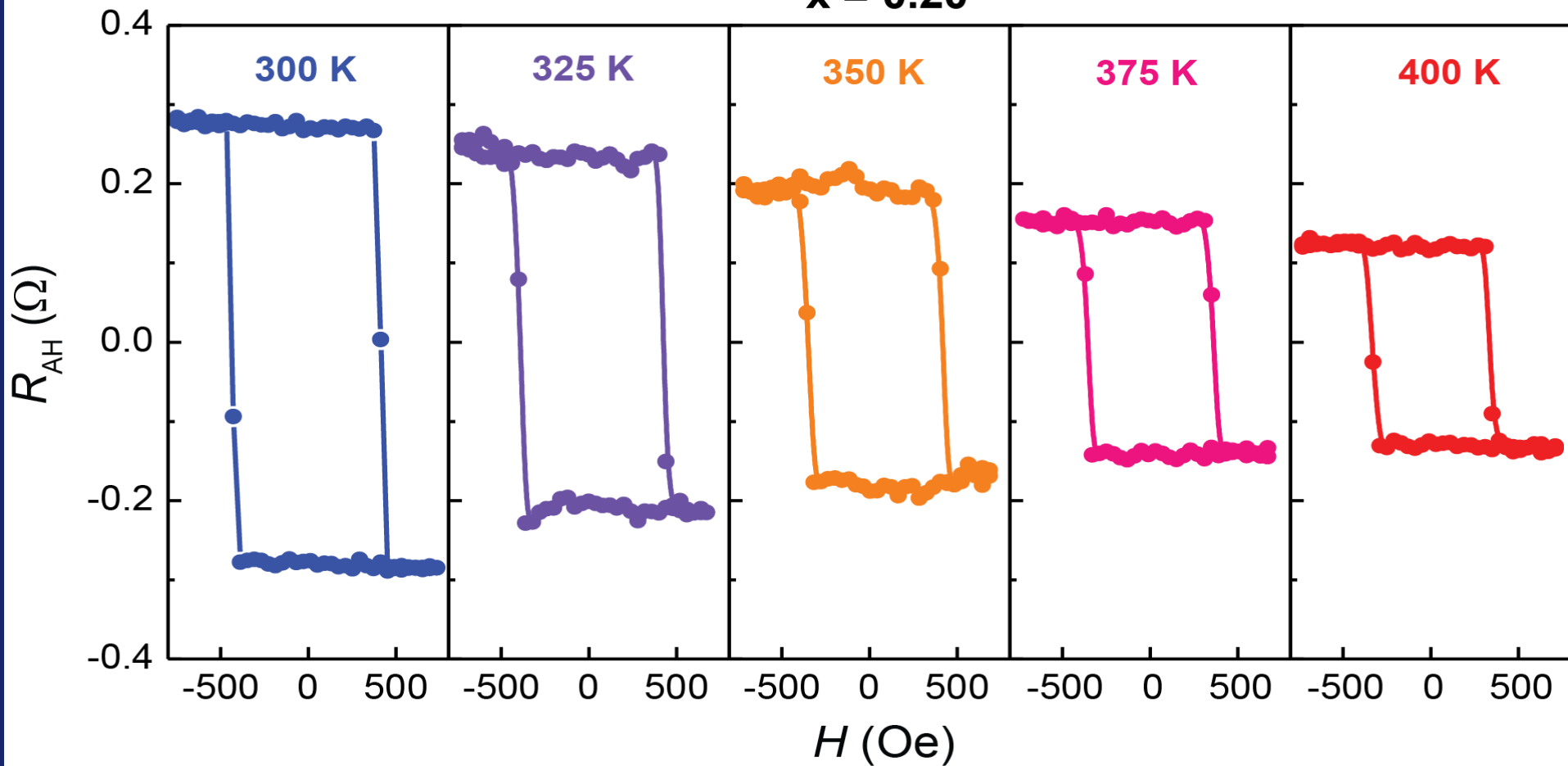
*Science Advances (Online June 2017)*



Spin polarization at the interface of TI/TIG heterostructure, indicates the interfacial induced FM phase in TI

# Temperature dependence of AHE response in TI/TIG

5QL $(Bi_xSb_{1-x})_2Te_3$     *p*-type

x = 0.20



- Perpendicular FM phase exists throughout the entire temperature range up to 400 K
- AHE resistance increase with decreasing the temperature

# Temperature dependence of AHE response in TI/TIG

5QL $(Bi_xSb_{1-x})_2Te_3$        *n*-type

**x = 0.30**


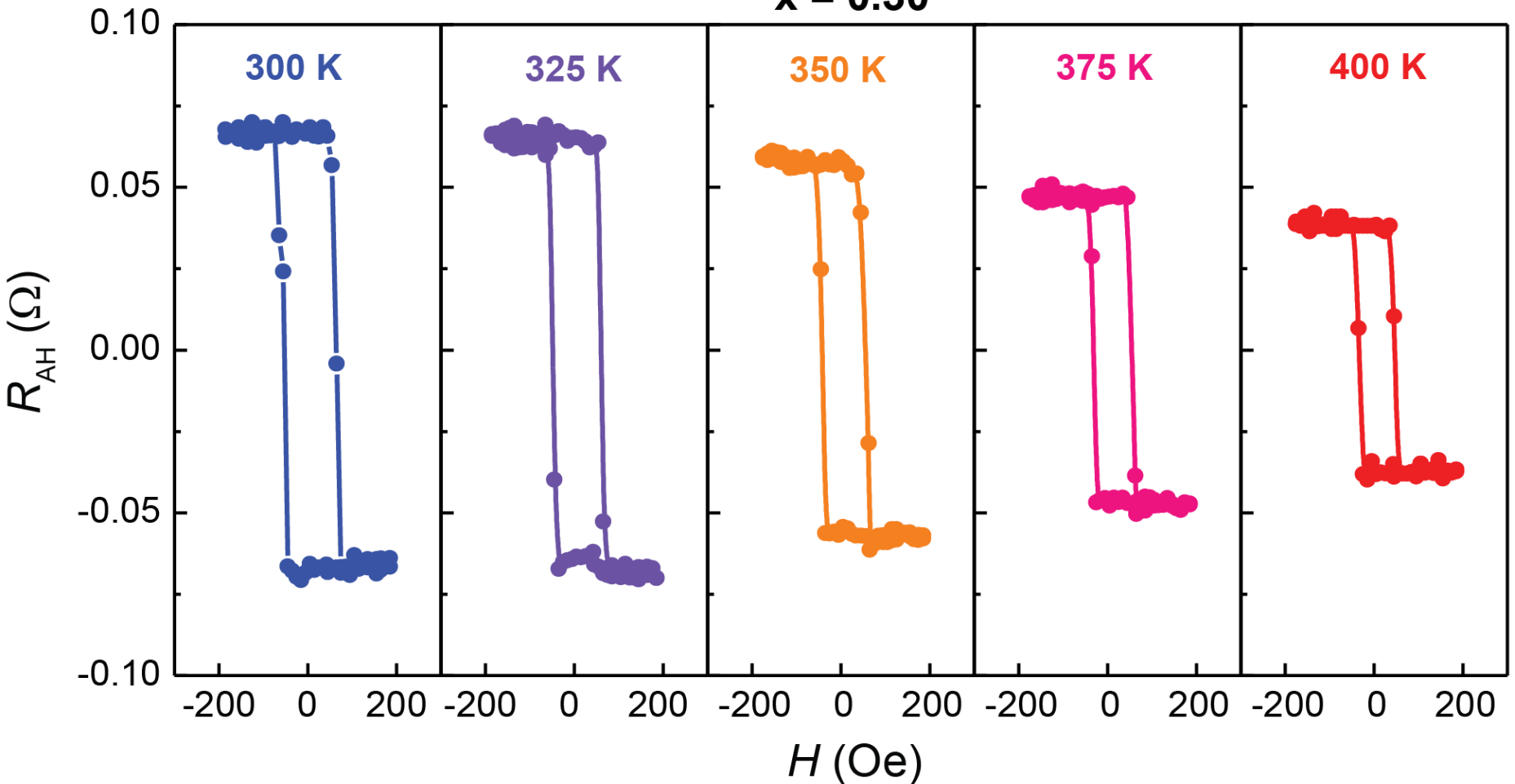
- Perpendicular FM phase exists throughout the entire temperature range up to 400 K
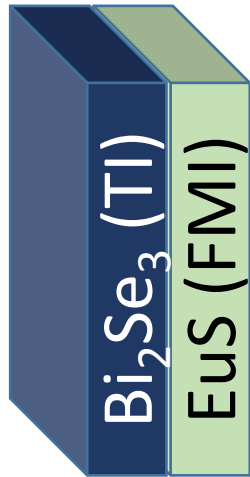- AHE resistance increase with decreasing the temperature

# Heterostructure FMI/TI bilayer – magnetic order by surface states

**(Kyungmin Lee, Nandini Trivedi)**
**Ohio State Univ.**

## Model:



Bi$_2$Se$_3$ (TI) / EuS (FMI)

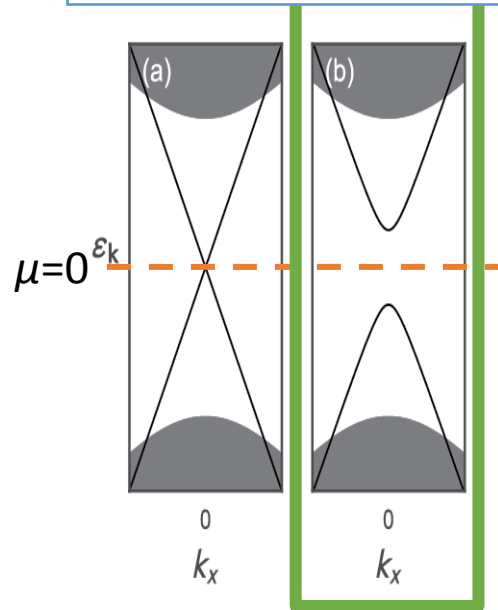Kondo coupling between spin and surface state

$$\mathscr{H}_{\text{Kondo}} = J \sum_{\mathbf{x}} \mathbf{S}(\mathbf{x}) \cdot c_{\mathbf{x}}^{\dagger} \boldsymbol{\sigma} c_{\mathbf{x}}$$

generates effective spin-spin interaction through RKKY-like mechanism

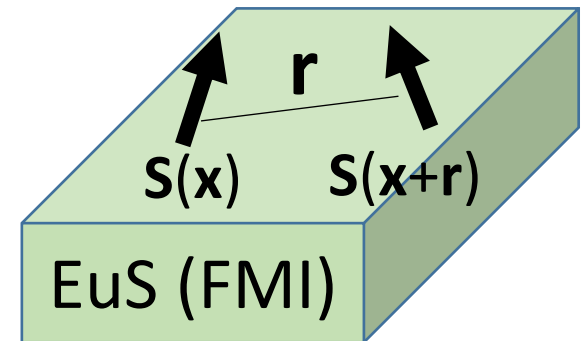Effect of **FMI on TI**: Gapping of topological surface states of TI



Before coupling to FM: GAPLESS

After coupling to FM: Massive Dirac

Effect of **TI on FMI**: Additional exchange and DM coupling generated between classical spins



S(x)    S(x+r)    r

EuS (FMI)

$$\delta F_2[\mathbf{S}] = -J^2 \sum_{\mathbf{x},\mathbf{y}} S_i(\mathbf{x}) S_j(\mathbf{y}) \chi_{ij}(\mathbf{x}-\mathbf{y})$$
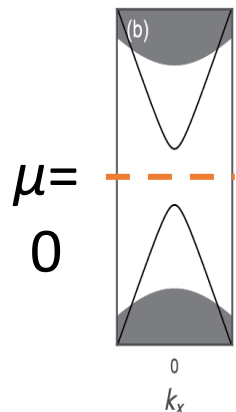
$$\tilde{J}_{ij}(\mathbf{r}) = -J^2 \chi_{ij}(\mathbf{r})$$

**χ : spin-spin correlation of surface states**

# Directional dependence of effective spin interaction
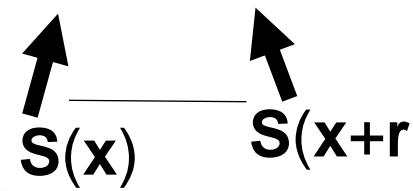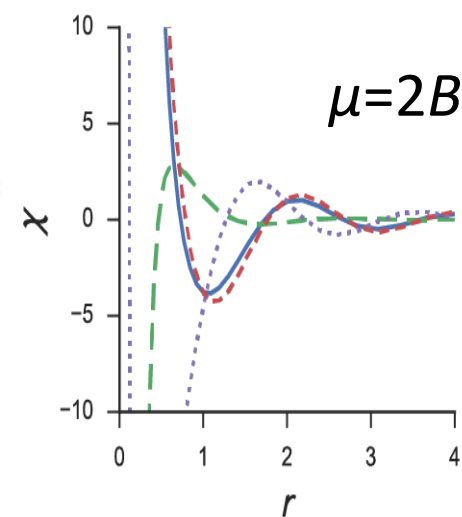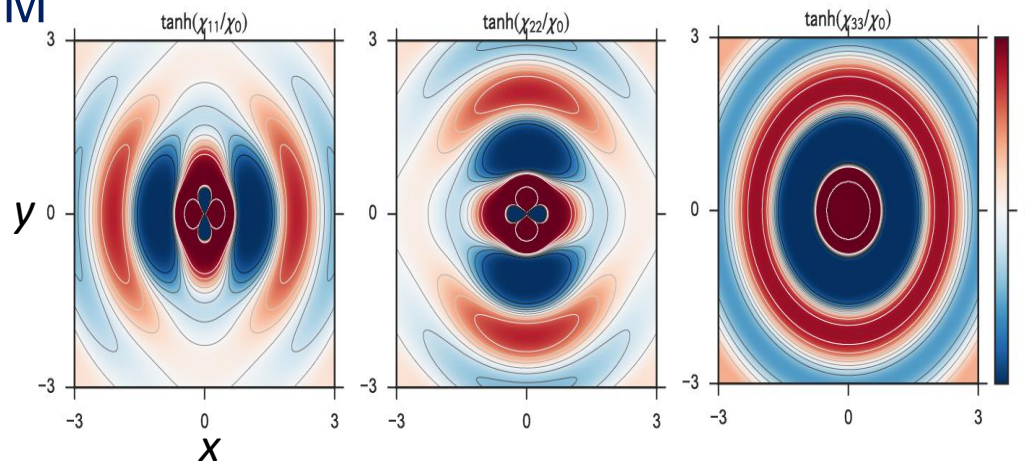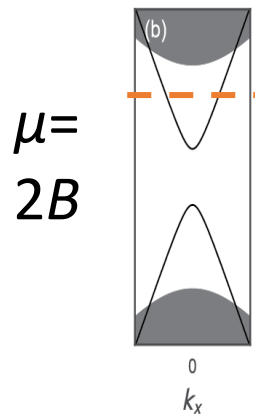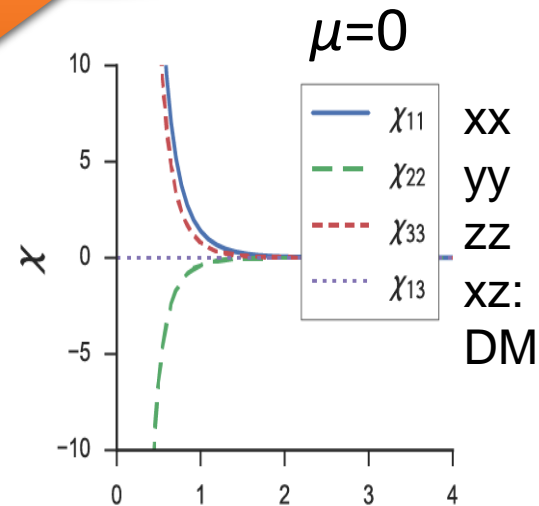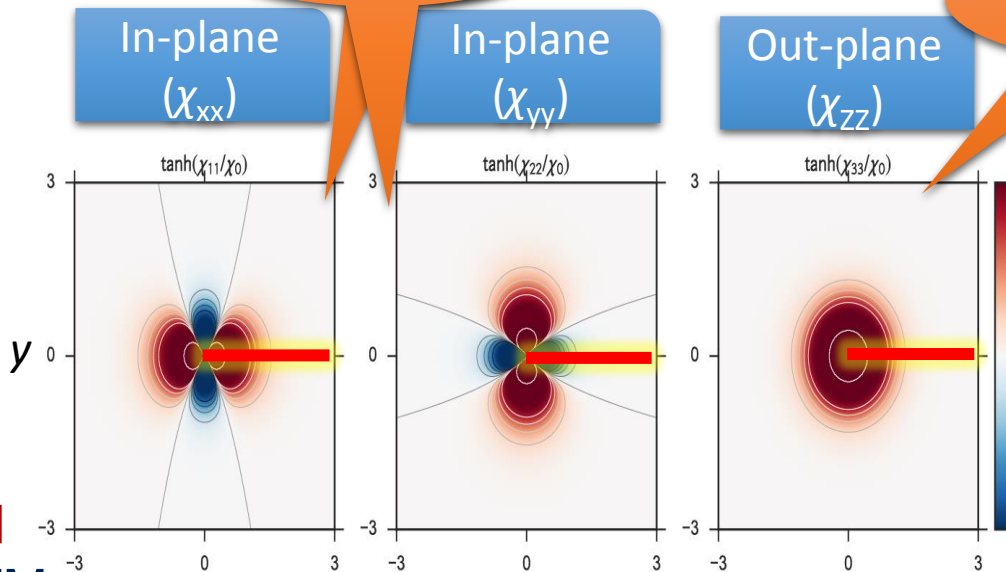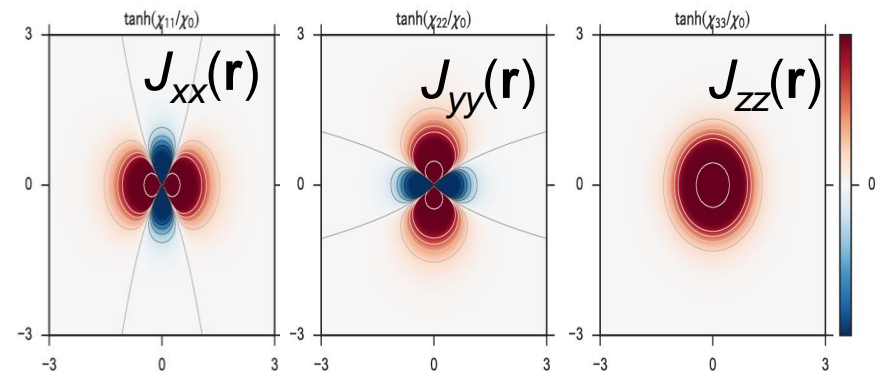
# Results for effective spin-spin interaction

- Effective spin interaction in FM mediated by the TI surface states can enhance $T_C$.

- Spin-momentum locking of surface state ➜ highly anisotropic spin interaction (RKKY of spin-degenerate metal is isotropic)

- "Frustrated" in-plane vs. stable ferromagnetic out-of-plane interaction ➜ consistent with out-of-plane magnetism at interface – exptl. obser.

- Oscillation in spin interaction as function of distance ➜ Possibly sensitive to lattice constant change

- Both Heisenberg and Dzyaloshinskii-Moriya present ➜ Possible skyrmion phase(?)

- Result summary

| | (Anisotropic) Heisenberg | Dzyaloshinskii-Moriya |
|---|---|---|
| $\mu$=0 | - Longitudinal: **FM**<br>- In-plane transverse: **AFM**<br>- Out-of-plane: **FM** | $J_{DM}$=0 |
| $\mu$=2 B | - Friedel oscillation<br>- Same as $\mu$=0 at short distances | $J_{DM}\neq$0 |



$J_{xx}(\mathbf{r})$  $J_{yy}(\mathbf{r})$  $J_{zz}(\mathbf{r})$

$\tanh(\chi_{11}/\chi_0)$  $\tanh(\chi_{22}/\chi_0)$  $\tanh(\chi_{33}/\chi_0)$

# Summary

**Investigating TI quantum properties**

*REQUIRES* **high quality TI films and heterostructures**

○ **Ferromagnetic TI -** *transition metal doped*
**QAH state obtained**

**Chiral dissipationless edge conduction observed**

○ *-  TI proximity coupled to ferromag. Insul. - works*
**Domain wall chiral conduction observed**

**Ferromagnetic TI at RT –  interface driven**

QAH state is yet to be reached

# Custom Built Metal MBE

# Carl Zeiss Leo Supra 25
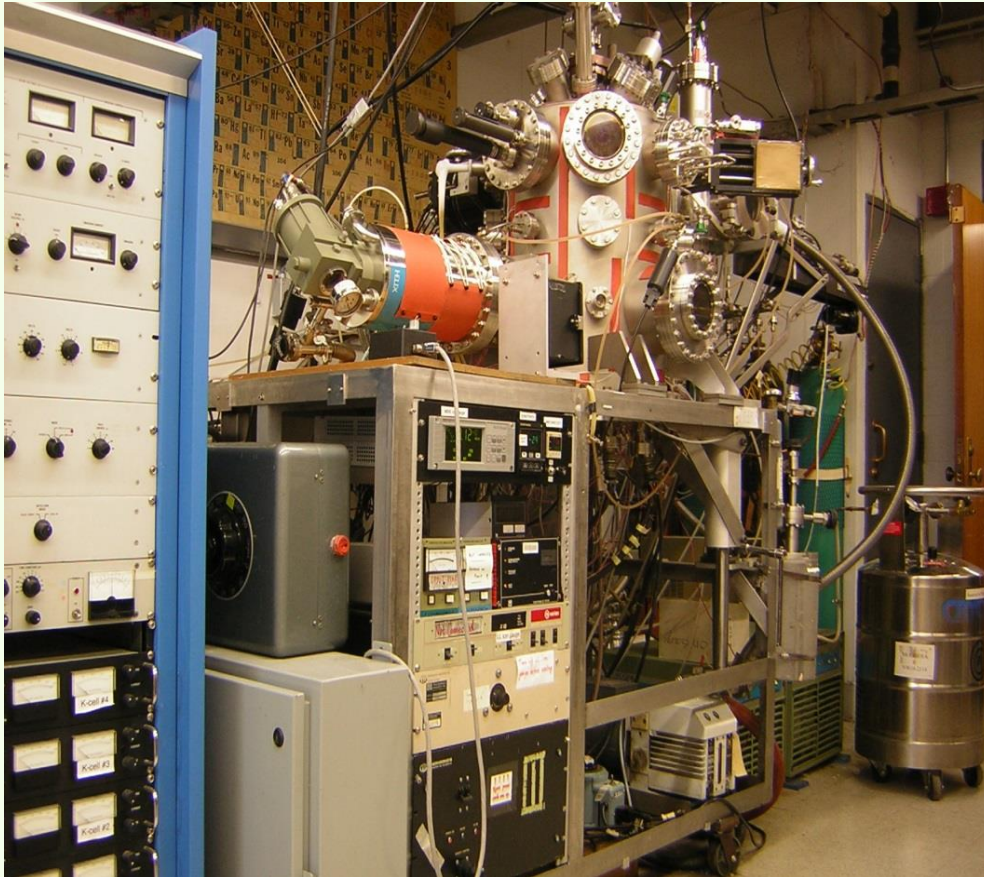




- $10^{-10}$ Torr, 14 sources, masks, plasma, insitu multilayers, sputtering,….. in-situ RHEED

- heating/cooling (80K to 1200K)…..
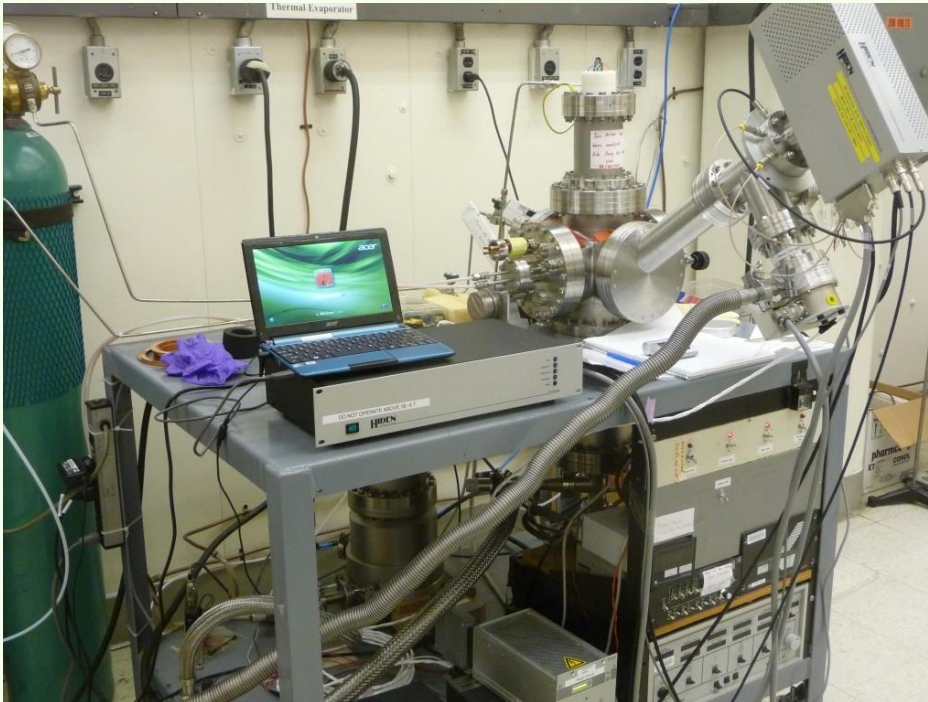
- angled deposition – nano structure creation

SEM (2nm)

Raith ebeam writing - nanopatterning (20nm features)

EDX – elemental analysis
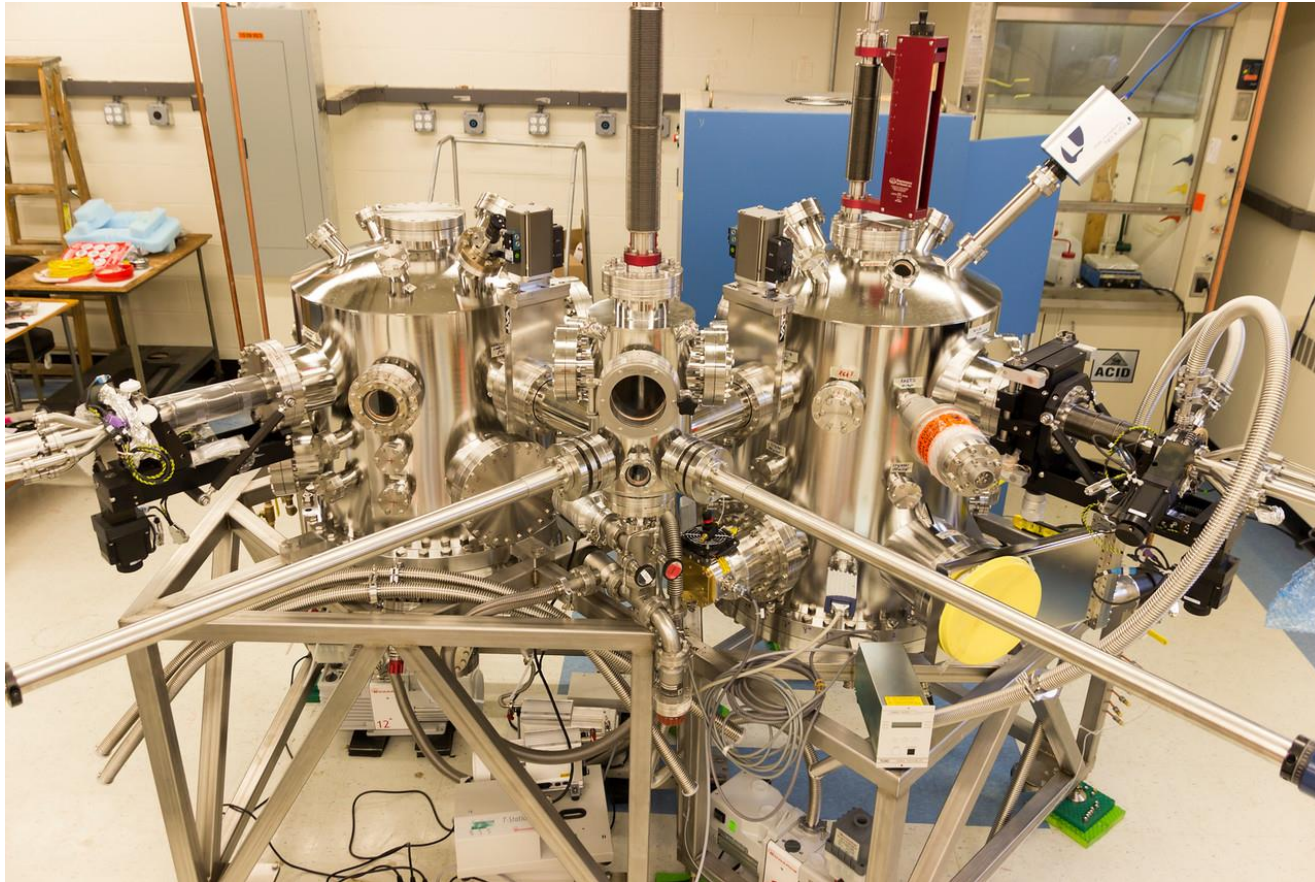
**Nano patterning:**
**Ion Miller with end point detector**

**Wire Bonder**





➡ **Low temp cryostats down to 400 mK, 8 tesla SC magnet and electronics for transport measurements**
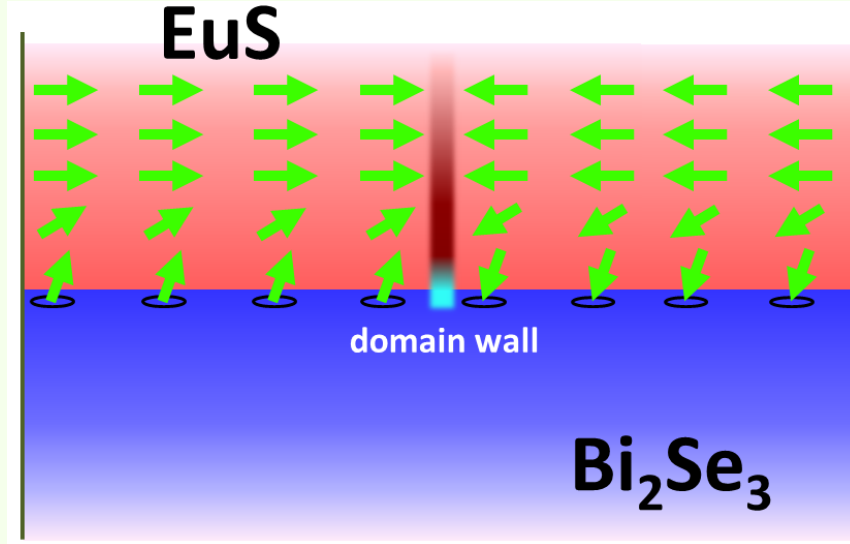
➡ **STM / c- AFM low temp probe, insitu sample transfer, 280 mK, 5 T in plane H (April 2015)**

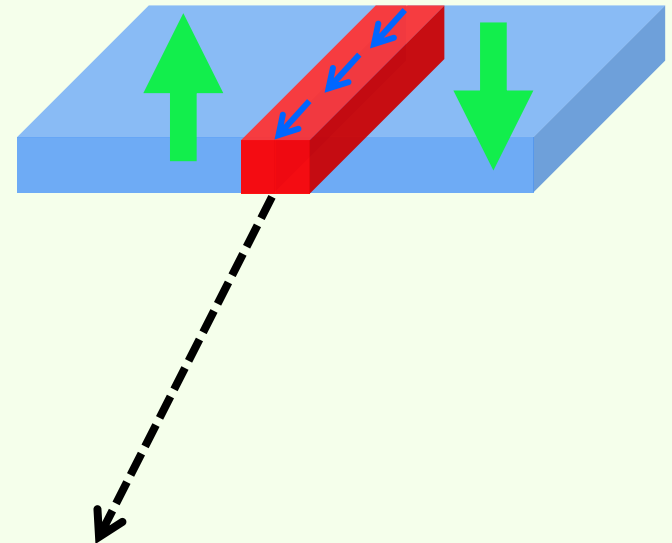# New cluster MBE – The Water Molecule !



**10 $^{-10}$ torr, 27 Sources: K-cell, e-Gun evapn, Sputtering**

**Heating/cooling (100K – 1200K), RHEED (*in situ structure*)**

**Sample transferable in vacuum (*'vacuum suitcase'* )**

**Insitu masking, angled evaporation (nano devices) ….**
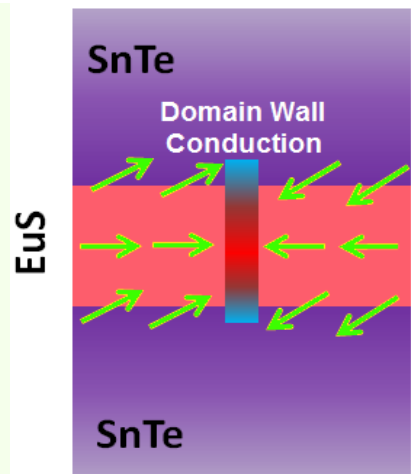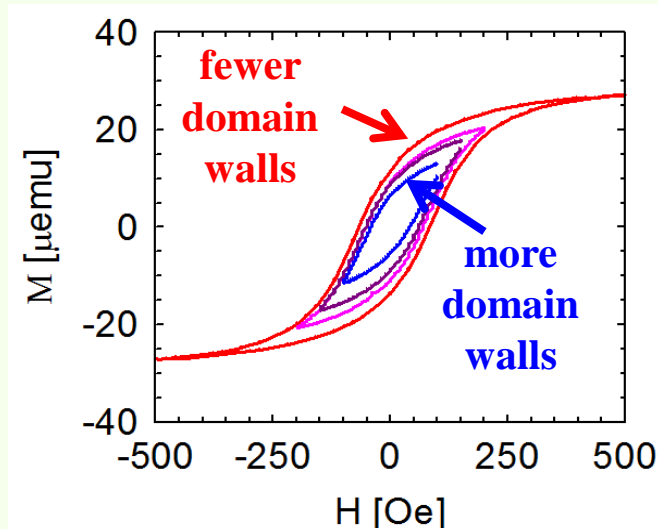
# What happens at the interface:



EuS

domain wall

$Bi_2Se_3$

$Bi_2Se_3$ top surface at coercive field $H_c$
(R minimum):

**Chiral conduction channel in domain wall (unique in TI)**

**P. Wei** *et. al.*, **PRL 110 (2013)**
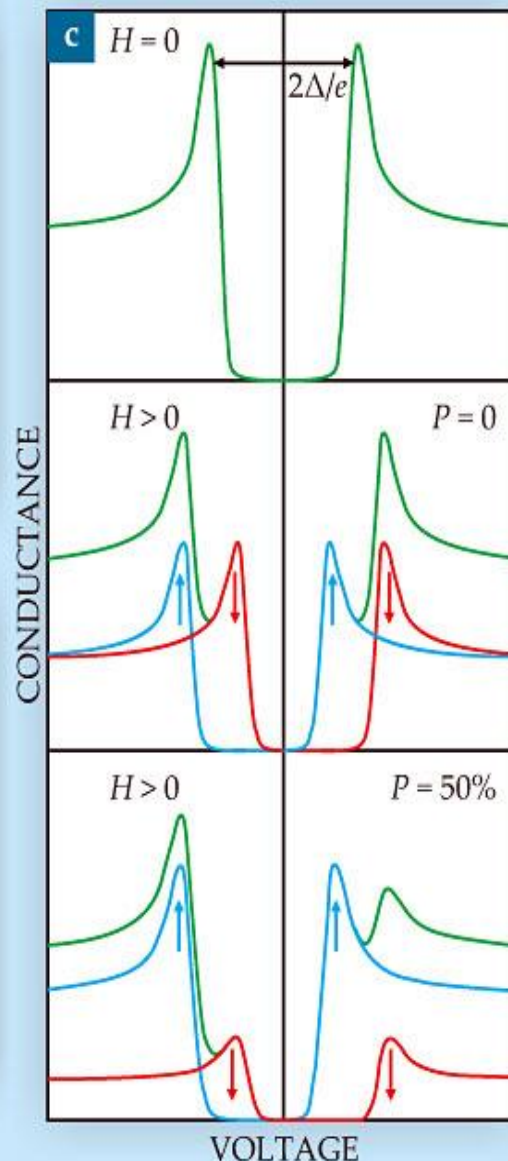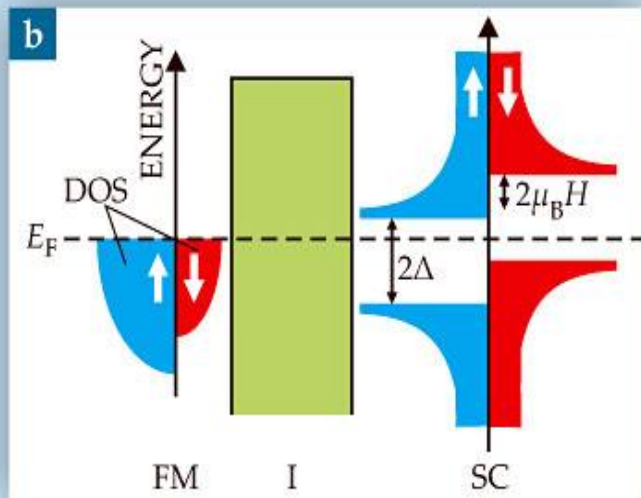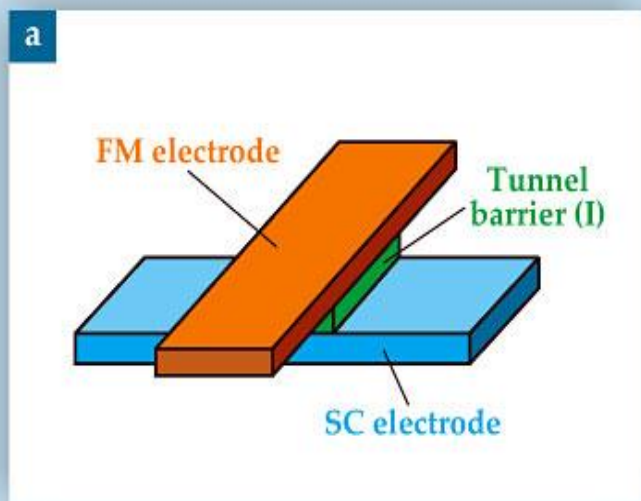
**Minor loops of SnTe-EuS-SnTe Trilayer**

**Resistance dependence on domain wall density at H = 0**
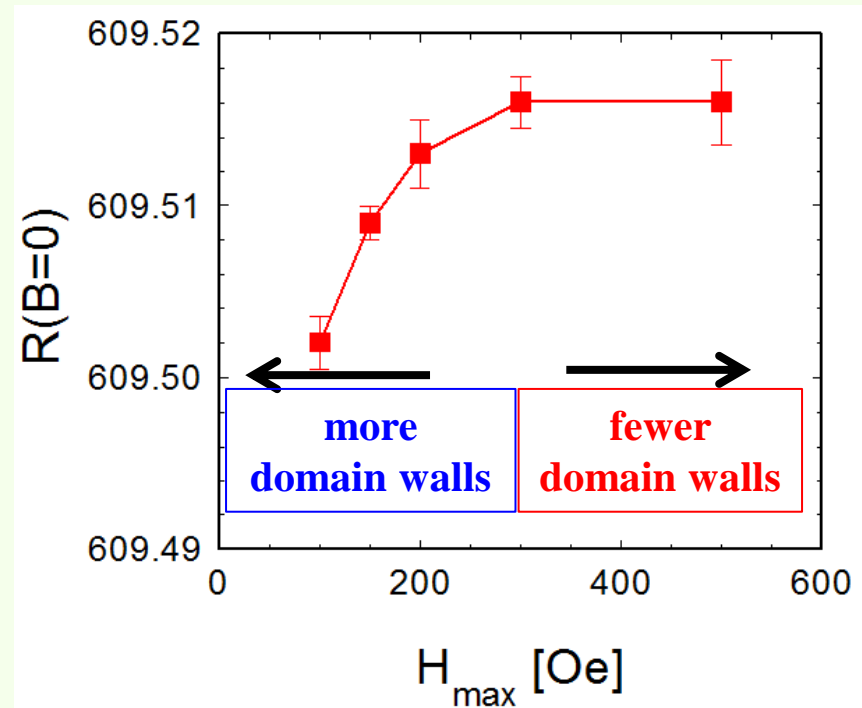


**Magnetic domain walls enhance sample conduction**

**Correlation between magnetic domain structure and transport**

**Badih A. Assaf**

# Meservey – Tedrow Technique of Spin Polarized Tunneling



**SC / Insulator / Normal metal tunneling**

**Supercond. energy gap**

**In a magnetic field**

**Zeeman split states in SC**

**SC / Insulator / Normal metal tunneling**

**SC / Insulator / ferromagnet tunneling**

**Tunneling e spin polarized**

$$P = ( n\uparrow - n\downarrow ) / ( n\uparrow + n\downarrow )$$

$$P \equiv \frac{(Nv^2)_\uparrow - (Nv^2)_\downarrow}{(Nv^2)_\uparrow + (Nv^2)_\downarrow}$$